ASSESSMENT TOOL FOR NUCLEAR MATERIAL ACQUISITION PATHWAYS

A Thesis

by

DAVID GRANT FORD, JR.

Submitted to the Office of Graduate Studies of
Texas A&M University
in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

May 2008

Major Subject: Nuclear Engineering

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Approved by:

Chair of Committee,	William S. Charlton
Committee Members,	Paul Nelson, Jr.
	David McIntyre
Head of Department,	Raymond Juzaitis

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ABSTRACT

Assessment Tool for Nuclear Material Acquisition Pathways.
(May 2008)
David Grant Ford, Jr., B.S., The University of Texas at Austin
Chair of Advisory Committee: Dr. William S. Charlton

An assessment methodology has been developed at Texas A&M University for predicting weapons useable material acquisition by a terrorist organization or rogue state based on an acquisition network simulation. The network has been designed to include all of the materials, facilities, and expertise (each of which are represented by a unique node) that must be obtained to acquire Special Nuclear Material (SNM). Using various historical cases and open source expert opinion, the resources required to successfully obtain the goal of every node within the network was determined. A visual representation of the network was created within Microsoft Visio and uses Visual Basic for Applications (VBA) to analyze the network. This tool can be used to predict the most likely pathway(s) that a predefined organization would take in attempting to acquire SNM. The methodology uses the resources available to the organization, along with any of the nodes to which the organization may already have access, to determine which path the organization is most likely to attempt.

Using this resource based decision model, various sample simulations were run to exercise the program. The results of these simulations were in accordance with what was expected for the resources allocated to the organization being modeled. The program was demonstrated to show that it was capable of taking many complex resources considerations into account and modeled them accurately.

ACKNOWLEDGEMENTS

I would like to thank my advisor and friend, Dr. William Charlton, for all of his understanding and support for the six years I've had the privilege of working for him. His knowledge and expertise has been a constant source of inspiration and a goal to which I hope to one day mirror. The staff at Los Alamos National Laboratory provided me a home for nine months during this research. I especially want to thank Lance Eaton and Arianne Eberhardt for their contributions and encouragements which helped make this work possible. Many thanks also go to my committee members, Dr. Nelson and Dr. McIntyre.

I would also like to thank those in my personal life for always believing in me and helping to push me to accomplish my goals. My parents David and Julie Ford have been a constant source of inspiration my whole life. All of the sacrifices you've made for me over the past 27 years have meant more to me than words can express. My brother Robert "Kevin" Ford helped provide the social release so often needed after a long weeks of often frustrating work. Finally, to my Fiancé Andrea, I don't believe I could have made it through this without your support and love.

Finally, and especially, I'd like to thank my grandfathers, Denzil Ford and Robert Clary, for instilling in me the drive to work hard, take pride in everything I do, and to serve my country to the best of my ability.

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CHAPTER I

INTRODUCTION

According to the President of the United States[1], "The greatest threat before humanity today is the possibility of secret and sudden attack with chemical, biological, radiological, or nuclear weapons." As early as 1993, Osama bin Laden expressed his desire to acquire nuclear weapons when he attempted to purchase uranium from the Sudan[2,3]. Thus, it is clear that there are organizations in the world intending to attack the U.S. with a nuclear device. What the U.S. must do to prevent such an attack is not only continue systematic dismantlement of the personnel, infrastructure, and resources available to organizations like Al Qaeda, but we also must develop an understanding of how such a sub-state organization might go about acquiring nuclear weapons given the resources available to them. Such an organization will likely follow a much different path to acquiring a nuclear weapon than a developed state. Understanding the opportunities available to these organizations and how those opportunities will drive any decision making process is vital to stopping any attempt such an organization might make to acquire a nuclear weapons capability. These decisions will involve technical assessments as well as organization and social science evaluations.

I.A. Background and Motivation

The proliferation of nuclear weapons has been a threat for as long as the weapons themselves have existed. In fact, the very first director of Los Alamos, J. Robert Oppenheimer, can be considered not only the father of the atomic bomb, but also the father of the field of nuclear nonproliferation[4,5]. After the first three weapons were detonated at the Trinity test site, Nagasaki, and Hiroshima, Oppenheimer recognized that these weapons will only increase in destructive force and that any state or organization with sufficient resources can develop them[4]. As a result, barely two months after Japan surrendered, he resigned as director of Los Alamos and spent the rest of his life trying to stop the spread of nuclear weapons.

This thesis follows the style of *Nuclear Technology.*

In order for a nuclear device to be constructed, kilogram quantities of particular non-naturally occurring material must be obtained. The two types of material used in nuclear weapons are Highly Enriched Uranium (HEU) and Plutonium (Pu).

Uranium is an element found in nature and is contained in the soil all over the world. However, certain geological formations contain a higher concentration than is average and these are the places where Uranium mines can be found. There are three isotopes of Uranium that occur in nature, Uranium 235 (U-235), Uranium 238 (U-238), and Uranium 234 (U-234). U-235 is the only naturally occurring fissile isotope and can be used in nuclear weapons. Only 0.0054% of natural Uranium is U-234, and only 0.72% of natural Uranium is U-235. Thus natural Uranium must be enriched to levels useful for nuclear weapons. This process can be done in a number of ways, all of which will be described later. Uranium must be enriched to greater than 20% U-235 and preferably greater than 90% U-235 to be weapons useable.

Plutonium is not found in nature. Thus all of the plutonium is man-made. Pu is produced by irradiating U-238 in a nuclear reactor. The U-238 is transformed into Pu via neutron absorption followed by two successive β^- transitions. The Pu that is produced in a reactor consists mainly of Pu-239, Pu-240, and Pu-241. Weapons grade Pu consists primarily of Pu-239. Commercial grade Pu has considerably higher levels of the other isotopes, some of which are highly undesirable in weapons material.

There are two types of nuclear proliferation[6]: horizontal and vertical. Vertical proliferation refers to countries that already have weapons producing more and/or better weapons. Horizontal proliferation refers to countries/organizations developing a nuclear weapons capability where there was none before. While vertical proliferation is a concern to the global community, it is only applicable to states. Controlling the buildup of nuclear weapons is the task of arms control treaties and makes use of agreements between responsible state entities.

When one speaks of horizontal proliferation, the problem becomes much more complex. Horizontal proliferation may involve irresponsible states (e.g. rogue states) or non-state actors. Previous efforts at halting horizontal proliferation have focused on securing commercial nuclear materials and on agreements between states. Rogue nations are unlikely to fulfill these agreements. Every case of horizontal proliferation or an attempt at it, in recent history (e.g. Iraq, South Africa, North Korea, etc.) has been covert. Discovering covert programs is very difficult and requires a detailed understanding of what to search for and what to protect. Early in the Cold War, the U.S. declassified details about using ElectroMagnetic Isotope Separation (EMIS) for enriching uranium because it was seen as an unlikely route for proliferation. However, it was discovered after the invasion of Iraq in 1991 that Iraq had a rigorous covert EMIS program[7]. Furthermore, South Africa's enrichment technique utilized an aerodynamic method which is shown to consume 1.5 times as much electricity as even a gaseous diffusion plant. This technique was successfully used to produce at least six covert nuclear weapons in South Africa[8]. The most likely explanation for this is that the aerodynamic method was the only method available to South Africa. South Africa had learned of the process from various German nuclear agencies. It is crucial to understand the paths available for horizontal proliferation to understand how to combat it.

Further consideration of the problem of horizontal proliferation leads us to consider the non-state actor. While there are no known cases of non-state actors acquiring nuclear weapons, or even enough useable material to fabricate a nuclear weapon, it is still important to consider them. As mentioned above[2,3], there are instances in which such organizations have attempted to acquire these materials. Because such organizations have shown interest in achieving a nuclear weapons capability through the theft or purchase of material (as opposed to producing it themselves), such pathways must be considered if these organizations are to be properly simulated.

An adversary (either state or non-state) desiring a nuclear weapons capability will follow a route based on an intelligent assessment of the resources available to them, their existing and expected capabilities, and the current situation. History has shown that these routes are logical but difficult to predict. They are difficult to predict because our understanding and knowledge of the adversary is incomplete and because the decisions they make are based on many variables (most of which are outside of our control).

The various requirements for obtaining a nuclear weapons capability are relatively well known, any nuclear fuel cycle textbook could be used to determine the facilities and commercial processes involved in producing enriched uranium and plutonium. The only difference between producing enriched uranium for a commercial power plant and enriched uranium for a nuclear weapon is the level to which it is enriched. Similarly, the only difference between producing weapons-grade plutonium and reactor-grade plutonium is the burnup level up the fuel. Additionally, there are even detailed accounts of the history of the Manhattan Project including rough schematics of some of the processes used[9,10], which could serve as a reference for any proliferator. Using these sources, one can devise the options available for the proliferator to produce a nuclear weapon. This will include more than simply determining what skill, material, or facility is required and deciding whether or not attaining it is feasible within one's constraints. A certain degree of forecasting must be used (e.g., just being able to obtain UF_6 is useless unless you can also obtain the means to enrich it). This is the main purpose of considering entire pathways to weapons material production as opposed to just the pieces along said path. While individual steps along each path are interesting and worth consideration, it is important to understand how an organizations resources will serve them along the path as a whole in addition to understanding how each step will be accomplished.

Thus, the growing problem of nuclear proliferation is one with many facets. In order for an analyst to truly assess the risk of any organization obtaining a nuclear weapons capability, they must know all of the characteristics of the organization and the resources required to develop the capability itself.

Intelligence estimates of foreign nuclear weapons programs go all the way back to the end of World War II. The U.S. and our allies developed estimates of how long it would take the U.S.S.R. to develop a nuclear weapons capability[11]. The best estimate was that they would not be ready until the mid-1950's at the earliest. These estimates were contrary to the fact that intelligence gathering clearly stated that the Soviets had the resources to begin producing plutonium on a large scale. Thus, the U.S. was generally surprised when the U.S.S.R. tested their first device in 1949.This shows that intelligence analysis must be performed on a macroscopic scale using all available information, and collection mechanisms should be based on how far along the path the adversary is. Had the U.S. intelligence services recognized earlier that the Soviet acquisition of enough high-purity calcium for refining large quantities of uranium metal implied that they would also need large quantities of uranium ore, then that particular piece of intelligence may have been gathered and the larger picture assembled in time to prepare the U.S. for a nuclear-armed Soviet Union.

This example of early intelligence estimates of nuclear weapons capabilities illustrates the need for big picture thinking and good intelligence gathering capability. Even if the other resources the Soviet Union had assembled were not discovered, it should have been within the ability of the analyst to provide an estimate for how much time would be required for each step along the way. In this manner, once any additional information was obtained, it could be assimilated into the big picture.

While the resources listed in the example above were all materials, the knowledge and skill sets required for a nuclear weapons program must also be taken into account when an intelligence assessment is done. An excellent example of this is the Pakistani program. Even while the Pakistani President had decided against a nuclear program, the minister of fuel and natural resources took it upon himself to begin acquiring the requisite skill sets by sending dozens of Pakistani scientists and engineers to the U.S. and other western countries for nuclear related education[12]. Individually, the education of these students is not significant. However, when taken together, the skill sets they were obtaining, the timing of the applications, etc. could have been a clear warning that a concerted effort was being made.

In the case of the South African nuclear weapons program, the resources available also played a key role in the path chosen. The South Africans began their program with a fairly robust industrial base upon which to build and had the added benefit of already having a nuclear energy and research capability. The increasing alienation they faced from the rest of the world (but especially the West) prompted the development of indigenous capabilities for their nuclear energy programs. These efforts culminated in the construction of an enrichment plant capable of producing enough material to fuel their commercial power reactors. When the vast uranium reserves, the existing nuclear energy infrastructure (including enrichment techniques), and the strong nuclear science base are considered together, the steps the South African government would have taken to build a nuclear weapon becomes clear.

In the work considered here, the most difficult part of a covert nuclear weapons program, obtaining the Special Nuclear Material (SNM), was addressed. SNM consists of plutonium or highly enriched uranium (HEU). A more rigorous definition can be found in any of the IAEA glossaries under special fissionable material, or just nuclear material[13,14]. The expertise, facilities, and material that must be obtained was developed in a manner that allows the prediction of the paths that might be chosen by any organization to obtain SNM. These paths include the resources required for each step including type of facility, skill set, or material. A decision analysis methodology was then developed to determine the most likely path an organization might take accounting for the resources available. Also, the organization's chance of success for traversing these paths is determined. This system is "big picture" oriented and considers how any part of a path affects the path as a whole. This enables the analyst to see how resources affect the long term plans of an organization. These tools were developed in a Microsoft Visio program using Visual Basic for Applications. The program allows an analyst to examine not only how SNM might be produced covertly, but what type of resources are required to do so and the best way any given set of resources might be used. All assumptions are explicitly stated and the tool is designed to be as transparent as possible.

I.B. Previous Work

This work encompasses modeling human and organization decision making processes, and how resources drive decisions. Presented in this section is previous work in decision theory and intelligence estimates pertaining to the resources required for nuclear weapons.

Many studies have focused on the various pathways that a proliferator might take to acquire a nuclear weapons capability. Some of these studies take a general approach to the problem and simply ask whether or not an anonymous country is more likely to produce a military controlled weapons complex or a series of civilian commercial facilities that are dual use. Einhorn[15] presents a number of options for how a country might use civilian facilities to forward their nuclear weapon aspirations. Many of his theories rely on the construction of civilian facilities and the resultant acquisition of nuclear experts that will come from operating those facilities. Once the knowledge base is acquired a country is free to withdraw from the NPT and actually produce weapons or simply make their enemies believe they possess nuclear weapons. Either is an effective deterrent according to Einhorn.

In July 2006 at the Center of Contemporary Conflict in Monterey California over 60 nuclear experts gathered to discuss what factors were most likely to influence motivations and capabilities for nuclear weapons proliferation in the next decade[16]. This group was comprised of professionals from all over the world who are all interested in halting the proliferation of nuclear weapons. The group managed to decide on 10 findings that it thought were significant to the international proliferation environment, 5 of which are of immediate interest to the work presented here[16]:

- *Apart from national leaders, influential figures both within states and at the international level can have a profound influence on states' decisions of whether and how to pursue nuclear weapons.* Knowing who these "mythmakers" are, the substance of their beliefs and claims, and the influence they have within a country at any given time can allow outside analysts and decision-makers to make more accurate predictions about the direction and speed of that country's attempts to obtain nuclear weapons.
- *"Disaffected disarmers," countries that abandoned nuclear bomb programs in the past but maintain some capability, are some of the biggest threats to restart nuclear weapons development programs***.** These countries can rearm quickly and may view themselves as major regional or international powers with a right to nuclear weapons. Even more significantly, the forces that motivated their original quest for nuclear weapons might reassert themselves as either the international security environment or domestic ruling elite changes.
- *Engaging diplomatically with actual or potential nuclear problem states can often buy enough time for the international community to develop long-term nonproliferation solutions, or for other unforeseen forces, such as the change of national leadership, or a severe economic crisis, to reorient the priorities of the proliferating state.* In this spirit, the Chinese consistently have attempted to engage North Korea as part of a longer-term effort to convince them to give up their nuclear weapons program. This strategy ultimately proved effective in

convincing Argentina, Brazil, and South Africa to abandon their nuclear weapons programs.

- *There are several new factors that could fundamentally change the proliferation environment in 2016.* Some observers worry that a renewed interest in nuclear energy could trigger a new round of nuclear proliferation. However, even a sharp increase in the demand for nuclear energy would not have a significant impact, because the lengthy lead-time for reactor production and commissioning means that 2016's reactors would already be well along the development stage now. However, in twenty years, real problems could emerge. More disconcerting is the potential rise of non-state actors in the supply side of the proliferation market, as evidenced by the A. Q. Khan proliferation network. Khan might have shown the way for more to follow.
- *On the whole, the U.S. intelligence community has done a good job of providing timely warning of significant proliferation events.* Despite well-known intelligence failures, such as incorrectly anticipating the timing of the Soviet Union's first nuclear weapons test or both sets of India's 1974 and 1998 nuclear tests, it has provided policymakers with an accurate assessment of proliferation dynamics. However, in many of these cases, policymakers have been unable (or unwilling) to effectively influence the proliferation motivations or behavior in question.

The first point goes towards decision theory. If we can assume that the "influential leaders" mentioned in the center's report have a bias for a particular path because they are already familiar with that path and know or suspect that it is going to work properly, then that piece of information is vital. Knowing what experience the scientists have in a particular organization will allow an analyst to make a better judgment of what that organization's capabilities are. For example, A.Q. Khan's familiarity with the gas centrifuge enrichment process from his time spent at the Physical Dynamic Research Laboratory, a subcontractor of Ultra Centrifuge Netherland, most likely played a very large role in his and ultimately Pakistan's decision to enrich uranium using that method.

The second point makes an excellent statement on ensuring that any analysis of nuclear pathways makes considering what capabilities already exist in a country a large factor. Any pathways analysis that is done for such a country or organization that does not take pre-existing capabilities into account would be incomplete at best, but most likely severely flawed.

The third point makes mention of something that certainly ought to be considered in any analysis of an organization, economic crisis. If the resources, whether they be financial, technical, industrial, etc. do not exist within the organization to produce a nuclear weapons capability, the chances of them doing so, or at least being successful, should reflect that.

The fourth point is similar to the second point as far as nuclear pathways analysis is concerned. The facilities and experience that exist within countries that have a strong nuclear power sector are certainly helpful to any weapons program. That is not to say that all the knowledge required for producing and maintaining a strong weapons program would be acquired while producing nuclear power. However, a country or organization with a strong history of nuclear power experience would begin the process of developing a weapons program with a significant edge over without.

The last point is especially important when an analyst considers not only what path an organization is most likely to take when attempting to develop weapons, but how likely they are to succeed. If an organization does not have the resources to accomplish their goals quickly or covertly, their chances of being caught must reflect that. History has shown that it is very difficult to hide such activities even with the resources available to a state.

There is a significant body of work available pertaining to decision making[17,18,19,20]. Cost-benefit analysis, Decision Trees, Paired Comparison Analysis, and many other decision techniques abound in the commercial world. These techniques can range from simple "is it cheaper to make it or buy it" techniques, to vastly more complex theorems capable of integrating hundreds, even thousands of variables into the decision making process including things such as cost, risk, payoffs, uncertainties, and justifiability[19]. It is especially important to note that most decision analysis techniques make use of this caveat: "the output will only be as good as the input." This means that even the most accurate decision model will be off target if provided with faulty information. This is especially important to note in a field as important as predicting decisions for nuclear weapons pathways. Faulty intelligence can literally mean life and death in these situations, and the confidence an analyst has in his intelligence must be high in order for these analyses to be considered useful.

One of the most interesting and applicable areas of research in decision theory is preference programming[20]. This uses a weighted analysis to account for the likelihood that a decision may not be based solely on "hard" facts but simple preferences an individual or organization might have. This would pertain to weapons pathways in that an organization may be much more likely to choose a path of which they've already obtained parts or of which opportunity has provided them parts (in the possible forms of materials, knowledge of certain processes in new members, etc). These relatively advanced methods of decision analysis provide many insights into how decision prediction can be accurate and provide many avenues through which analysts can justify and exercise their methods.

Fortunately most (if not all) of the decision analysis techniques are forward techniques. This means that they are mostly designed to assist an individual or organization in making their decisions based on a desired outcome forward in time, either through enabling them to determine what it is they really want, or to ensure their resources are used to their maximum potential. Thus, once we determine what the organizations resources and preferences (if any) are, then we can correctly model what their most efficient, and thus most likely, use of them will be.

The first attempt at automating the process of tracking the resources being acquired by a state actor that could be used for a nuclear weapons program was documented by Pacific Northwest National Lab (PNNL) in 1993[21]. The code they developed was designed to be used by inspectors in country to keep track of any activities that might be suspicious. This code was designed to keep track of any information found that might indicate a clandestine weapons program, and what types of activities they might be associated with. In this manner, the inspector and the IAEA as a whole would be able to more easily look at the "big picture" of what the country might be doing. This particular method of intelligence gathering would also lend itself well to gap analysis. For example, if one or even multiple pieces of information support the conclusions that the country in question is constructing a clandestine reprocessing facility, it should be relatively straight forward to determine which additional pieces of information should be obtained or which tests should be run to definitely say whether or not this is the case.

One of the best ways to approximate time to completion estimates were to introduce learning curve models[22]. These models allow for accurate estimates of production times for pathways analysis as well as good justification for many of the estimations made. Similar to decision theory, learning curve literature is quite abundant[22,23]. Also, there is precedent for applying learning curves to the process of resource and time estimations within a nuclear weapons pathways analysis[22]. This allows for not only a robust analysis that will be capable of making accurate estimations, but will also incorporate yet another tested approach to resource management theory. The U.S. government had a valuable book prepared by the Rand Corporation on the subject[23]. While most of this document consists of facts and figures not necessarily applicable to this work, the theory section does an excellent job of detailing the various approaches to learning curve models and what the appropriate uses of them are.

One good source of previous work in estimating the resources that are actually required to obtain a covert nuclear weapons capability can be found in an Office of Technology Assessment report to Congress from 1977[24]. While there are multiple sources for estimating the resources spent during the U.S., Soviet Union, South African, Iraqi, etc weapons programs, none of these are a complete picture of all the resources required to covertly produce SNM through all of the various ways that are possible. This 1977 report attempts to obtain dollar figures associated with the types of facilities that would be required. These estimations are made through expert elicitation from all of the intelligence resources available to the office. This provides a good starting point for the estimations included in this work, when combined with inflation and the various indexes that exist to account for construction cost increases over the last 30 years.

The literature that exists concerning whether or not a terrorist organization would be capable of constructing a nuclear device largely consists of qualitative analysis[25]. Some of these documents focus on the technical difficulty of designing and assembling such a device assuming the organization could obtain the requisite materials[25], others take the availability of the SNM as their main focus[26,27], while others take a look at the process as a whole[28]. The overlying assumption in all of these reports is that, were a terrorist organization able to acquire a nuclear weapon, they would certainly use it. This being the case it is of the utmost importance that all nuclear material is accounted for and properly safeguarded.

CHAPTER II

NETWORK DEVELOPMENT

II.A. Network Construction

A detailed network illustrating all possible paths for an organization to acquire the SNM needed for a nuclear weapons capability was created based on expert knowledge and using historical and hypothesized paths. The network includes all relevant expertise, facilities, and materials to assemble the correct, coherent paths. These expertise, facilities, and materials are displayed as nodes on a network. In order to develop a complete yet concise network consisting of every pathway SNM may be attained, the level of detail of the system had to be balanced with the information available for characterizing the nodes in the network.

The network was developed by beginning with a top-level network (Figure 1) which included very brief detail. The nodes in this network where then expanded to include additional detail (Figure 2). This process was continued until a network with sufficient detail to fully characterize paths was created with a concise number of nodes. The entire network is shown in Figure 3.

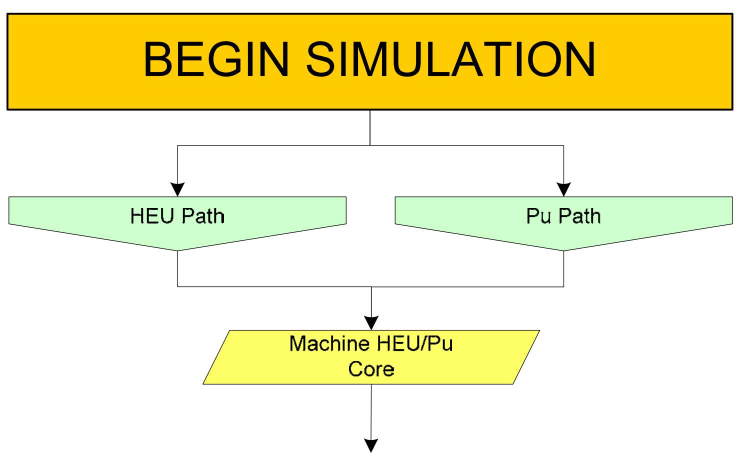


Figure 1. Initial top level network

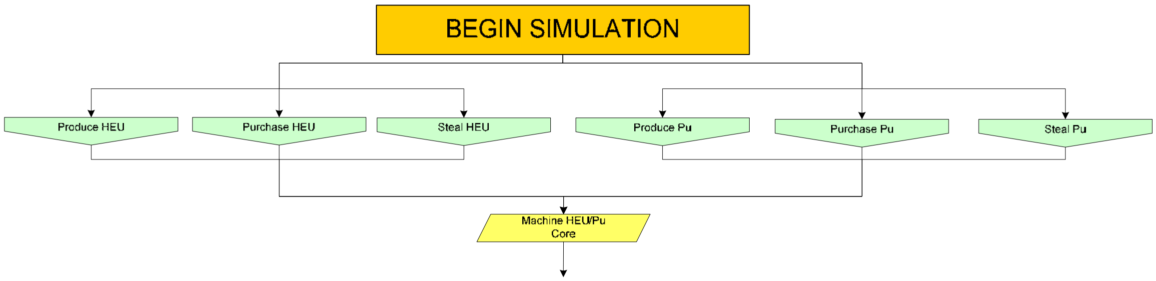


Figure 2. Expanded network with increased detail

In order to produce any material a modern organization must develop the basic skills necessary to facilitate producing the material of interest, build the required facilities, develop more refined skills during the process, and then use the facility and skills to produce the material. The network contains 3 types of nodes: Skills, Facilities, and Materials. These three node types are shown in Figure 4.

The organization will begin at the top of the network and choose whether to seek HEU (Figure 5), Pu from an LEU reactor (Figure 9), or Pu from a natural U reactor(Figure 12). If the organization chooses HEU they must then decide which material they wish to begin with. For example, the U.S. began with raw Uranium ore taken directly from the earth as can be seen in Figure 6. This includes many conversion and process steps that must be completed in order to produce the final product of HEU, however it involves building the capacity to continue producing weapons material, something a nation may be very interested in. An organization interested in a smaller required infrastructure may choose to simply obtain material that can be enriched directly, most of these pathways begin in Figure 7 with the exceptions of the EMIS path in Figure 6 and the AVLIS path in Figure 8. These paths require acquisition of material that has been pre-processed and relies on continued availability of this material for a sustained weapons program but not all organizations may be interested in sustainability. The shortest paths available to the organization are shown in Figure 8. These paths involve the acquisition of material that has gone through many processes. All of the material that has already been enriched is shown in this area of the network, cutting out most of the effort that must be done to prepare the material for a weapon, leaving only possible conversion to a metallic form and the casting and machining process final processes.

If the organization were to choose a Pu weapon they are still faced choosing the type of reactor that will be used in the production of the Pu, one fueled with LEU or Natural U. The LEU path shown in Figure 9, Figure 10, and Figure 11 has been included mostly for completeness to account for an organization that may already have access to such a reactor, the fresh fuel for one, or spent fuel from one. If an organization were to produce the capability to produce its own LEU, as shown in Figure 10, it is much more likely to simply use that capacity to produce HEU. However, if the organization can obtain the necessary material to run an LEU reactor through acquisition of material at the top of Figure 11 then it would be capable of producing Pu. Once the Pu has been produced it must still be chemically separated from the spent fuel and converted into a metallic form for casting and machining into the core of a nuclear weapon. The organization also has the option of bypassing as much infrastructure as possible by acquiring material that has already been processed as can be seen at the top of Figure 11.

If the organization chooses to produce Pu in a reactor fueled with Natural U then it begins at the top of Figure 12. The organization must first choose how much infrastructure it is capable or willing to acquire and obtain material accordingly. The organization may opt to build all necessary facilities and begin with raw Uranium out of a mine. This pathway will necessitate all of the conversion and process steps required for producing natural uranium fuel, a reactor, and the separation processes required to extract the Pu out of the spent fuel. This type of program reflects what a nation state might wish to accomplish to produce large quantities of Pu. However, a small organization may acquire Pu with a minimal amount of infrastructure by obtaining material from the top of Figure 12, bypassing entire facility requirements all together. Such an example might include the theft or purchase of Pu that has already been separated from spent fuel but still exists in a form unsuitable for weapons purposes (most likely in solution). This material must then be converted into metallic form for casting and machining of a pit for a nuclear device. This type of infrastructure is much more reasonable for an organization of modest size that does not wish (or have the capability) to build a nuclear reactor.

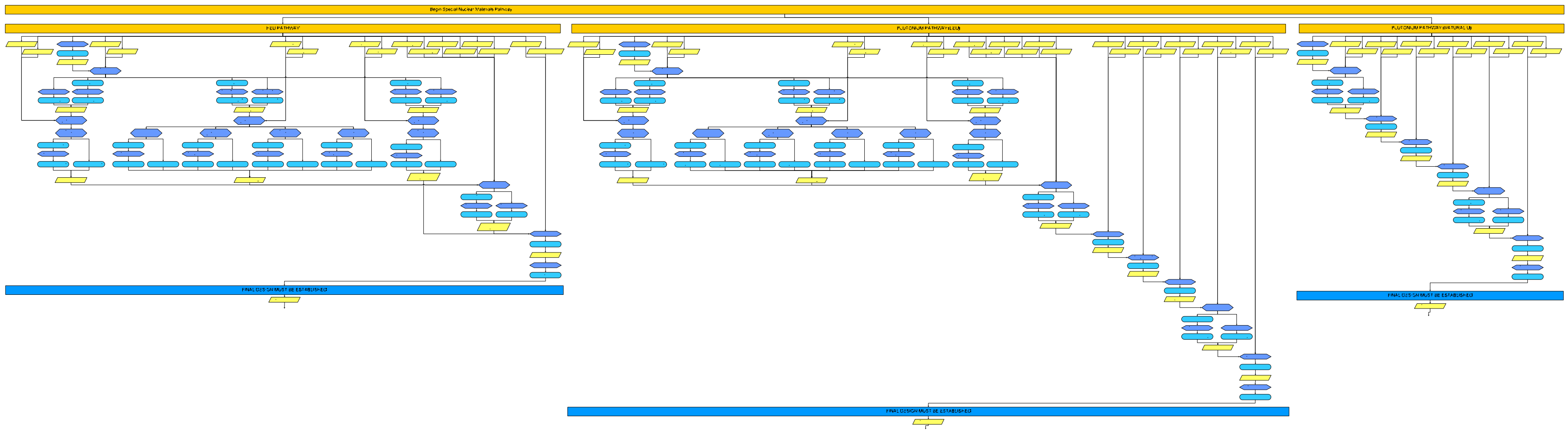


Figure 3. The complete network for SNM acquisition

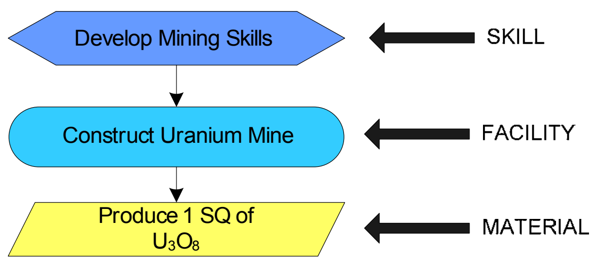


Figure 4. Example showing the three basic node types

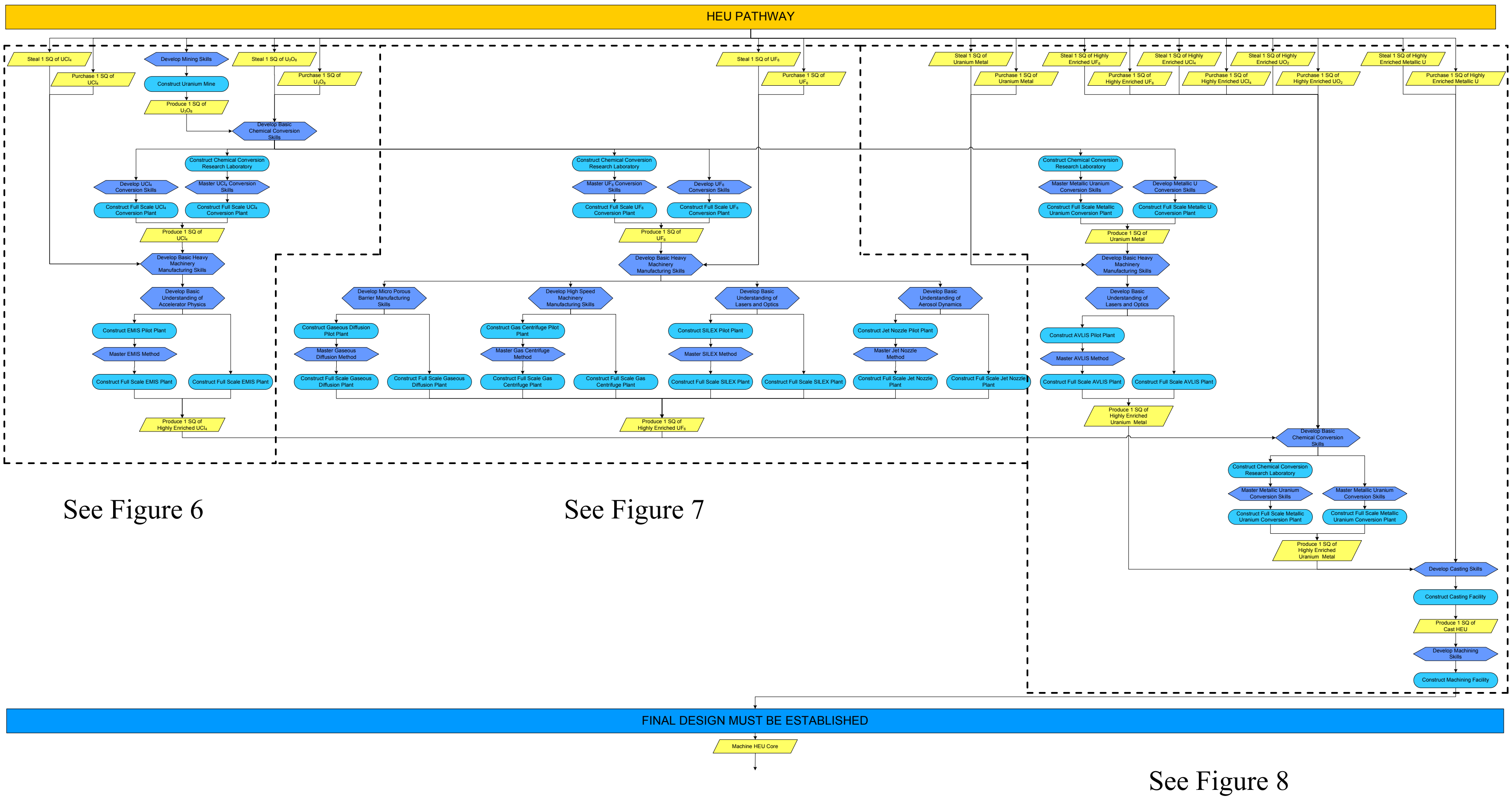


Figure 5. HEU Section of the Network

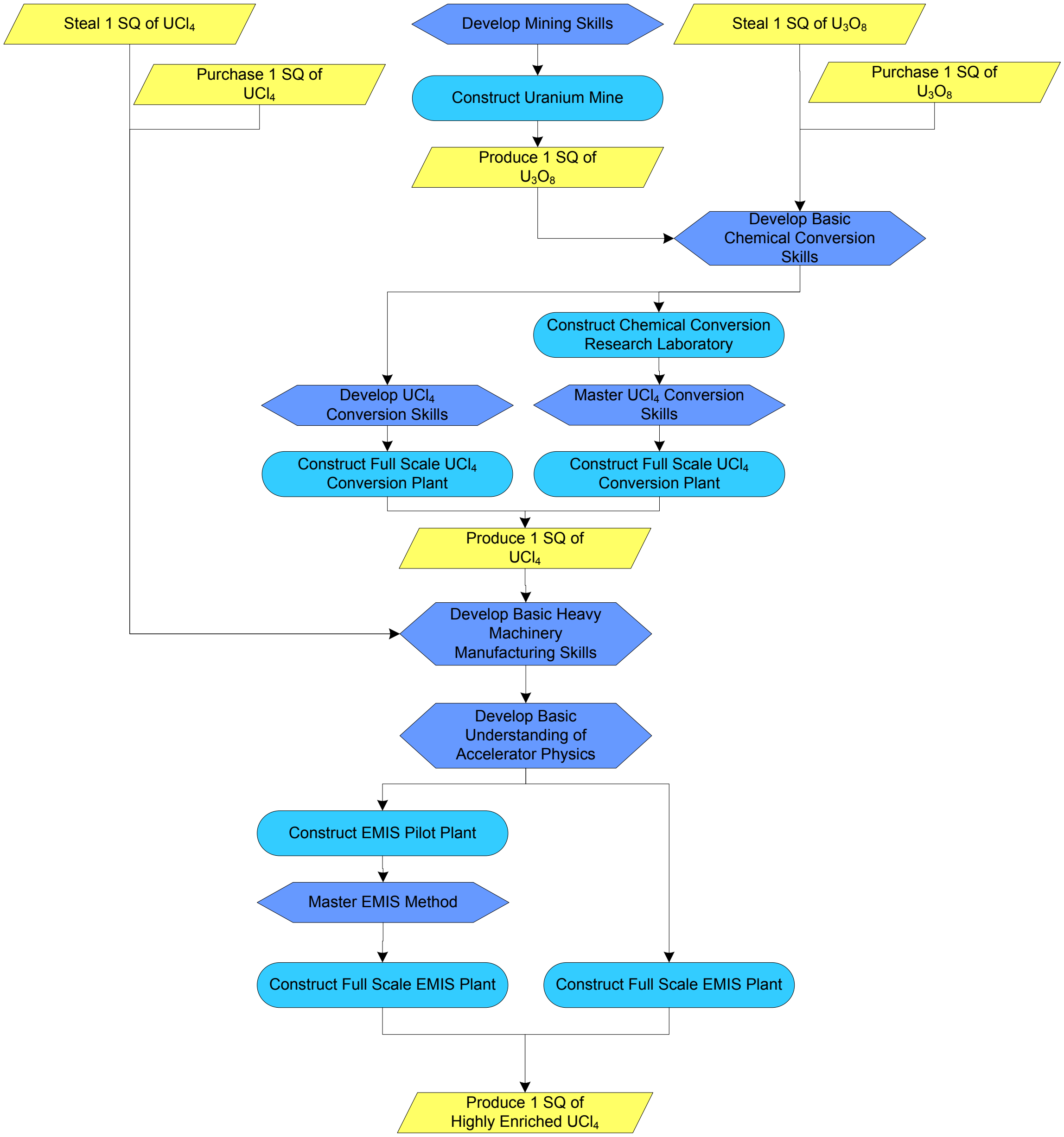


Figure 6. First Section of the HEU portion of the network

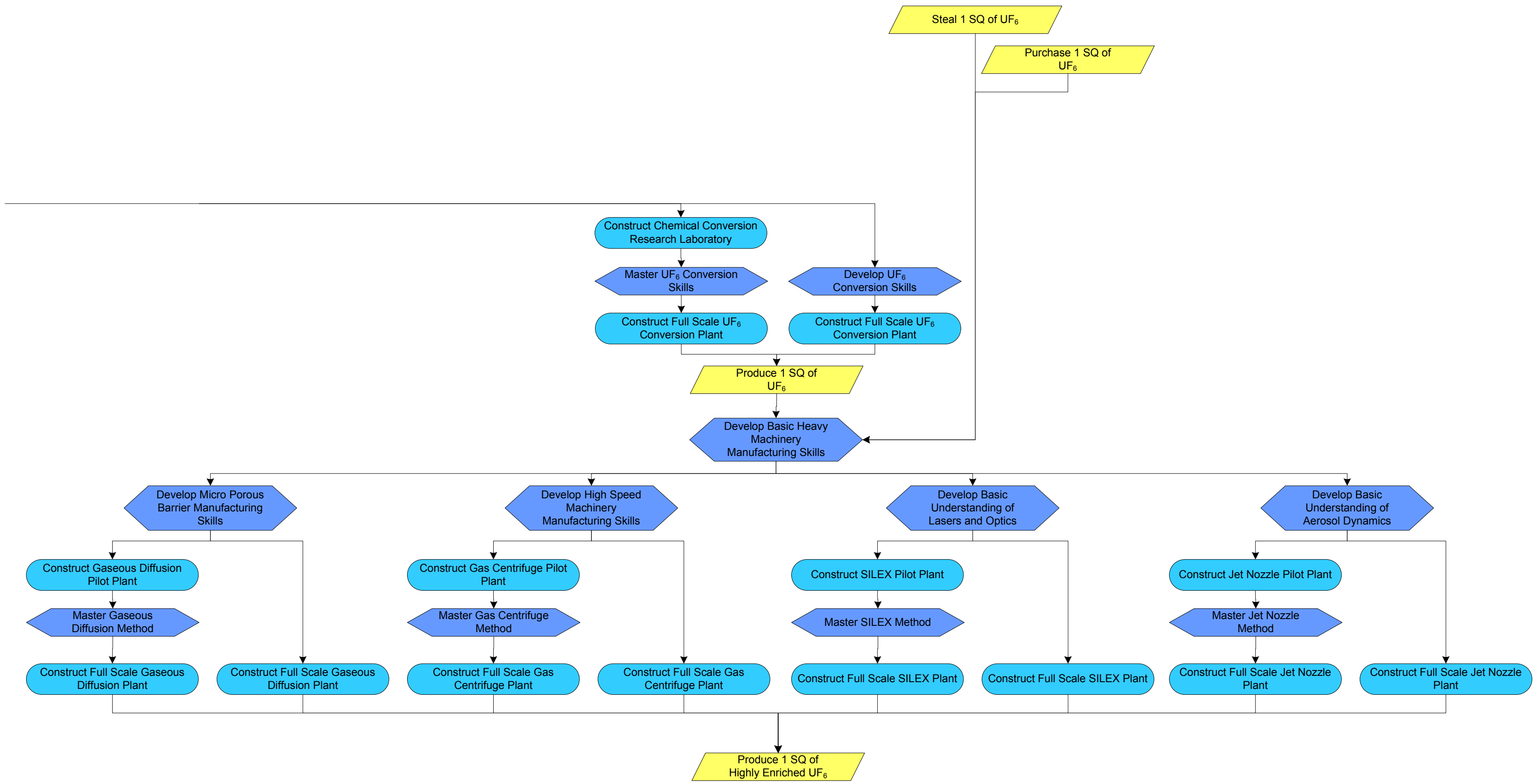


Figure 7. Second section of the HEU portion of the network

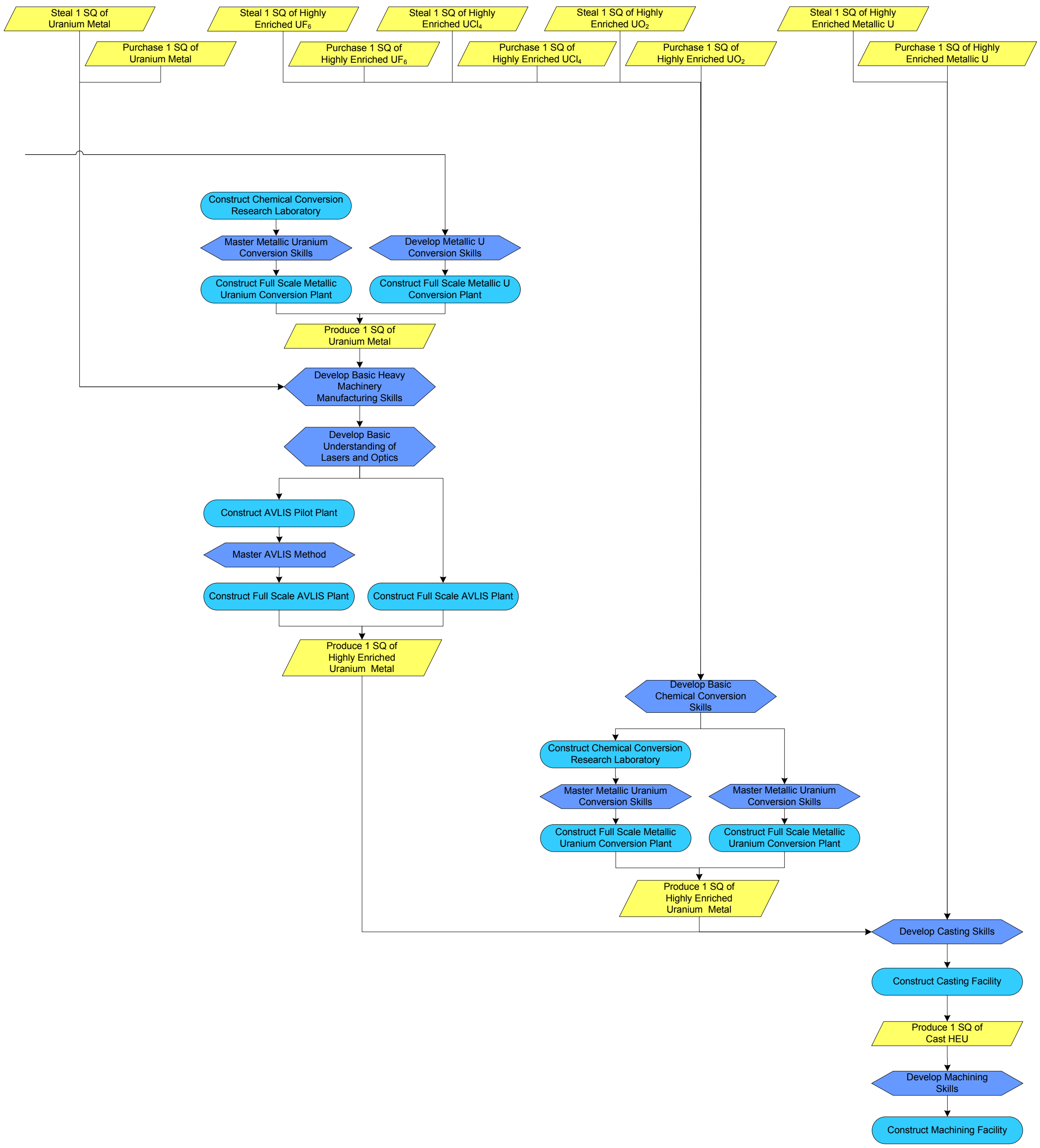


Figure 8. Last section of the HEU portion of the network

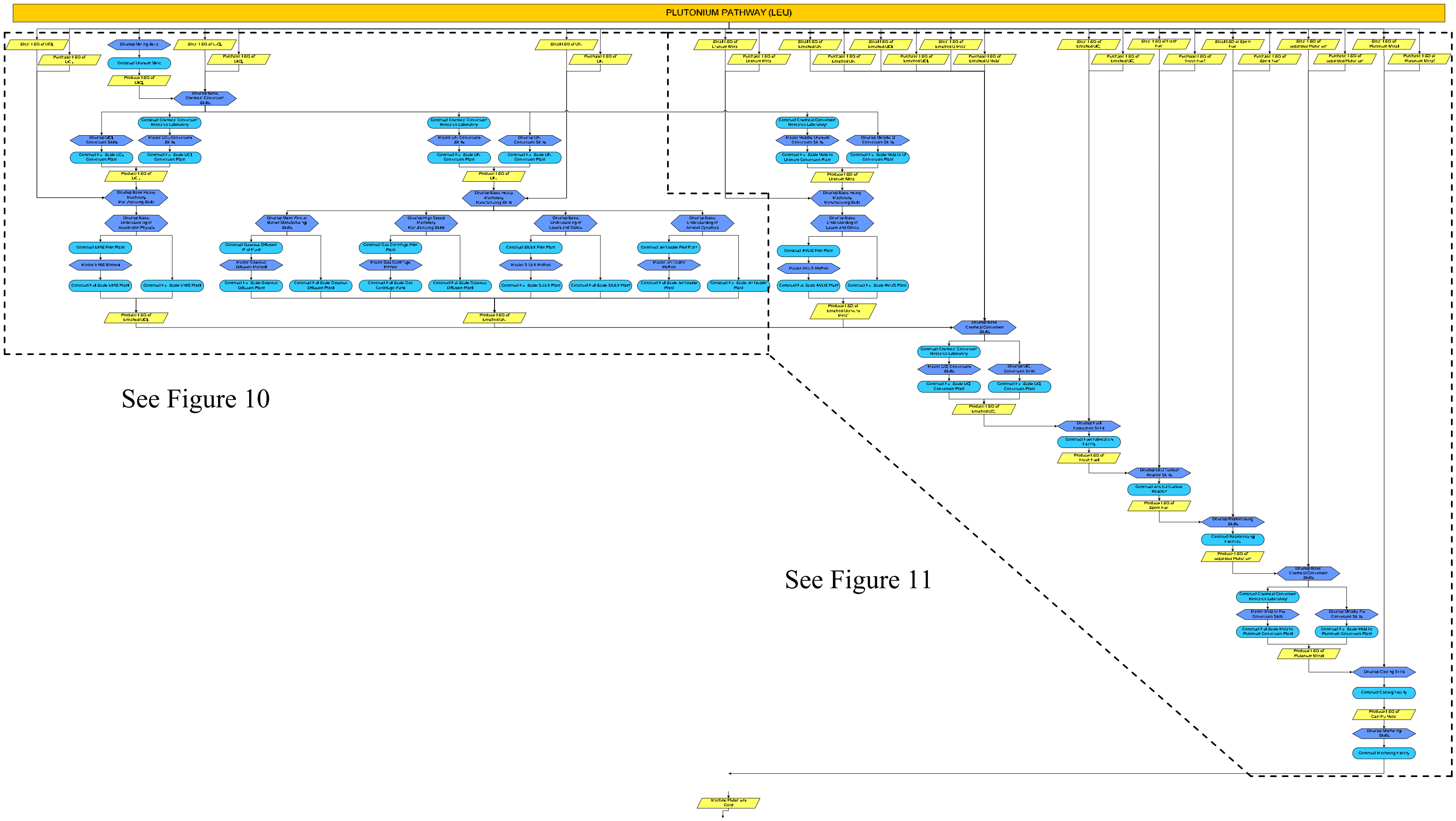


Figure 9. Plutonium section of the network produced via LEU

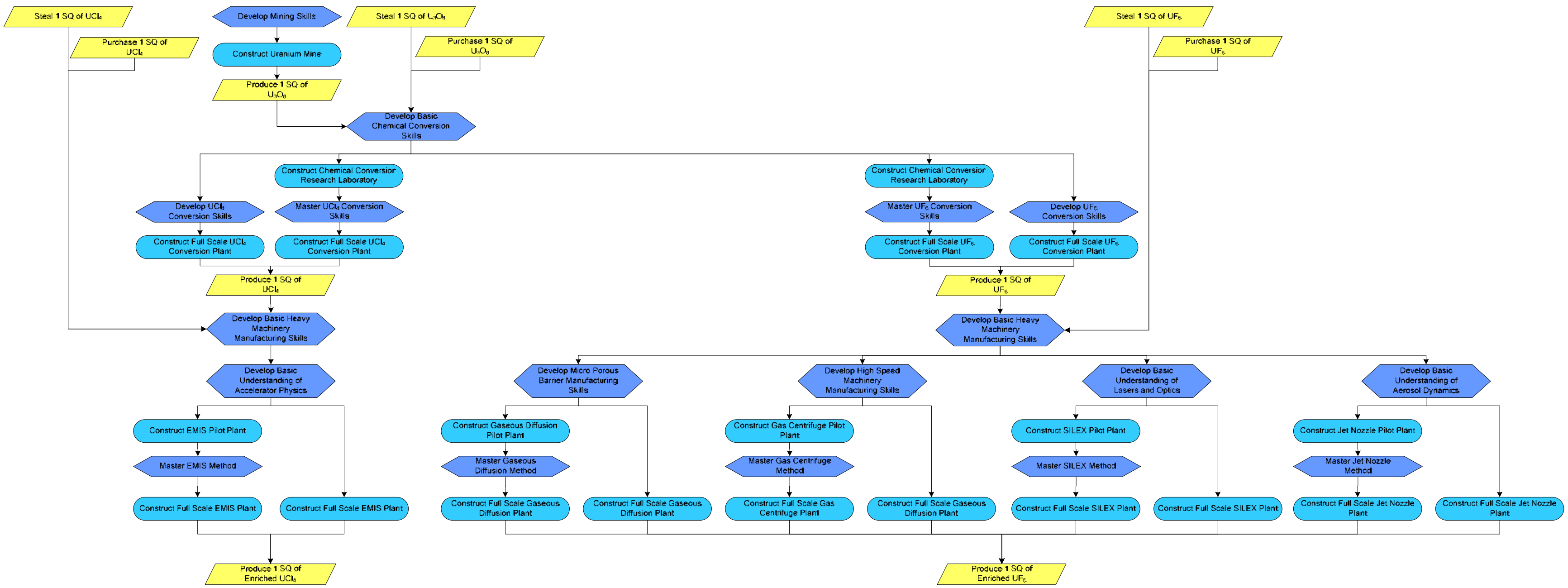


Figure 10. First section of the Pu (LEU) portion of the network

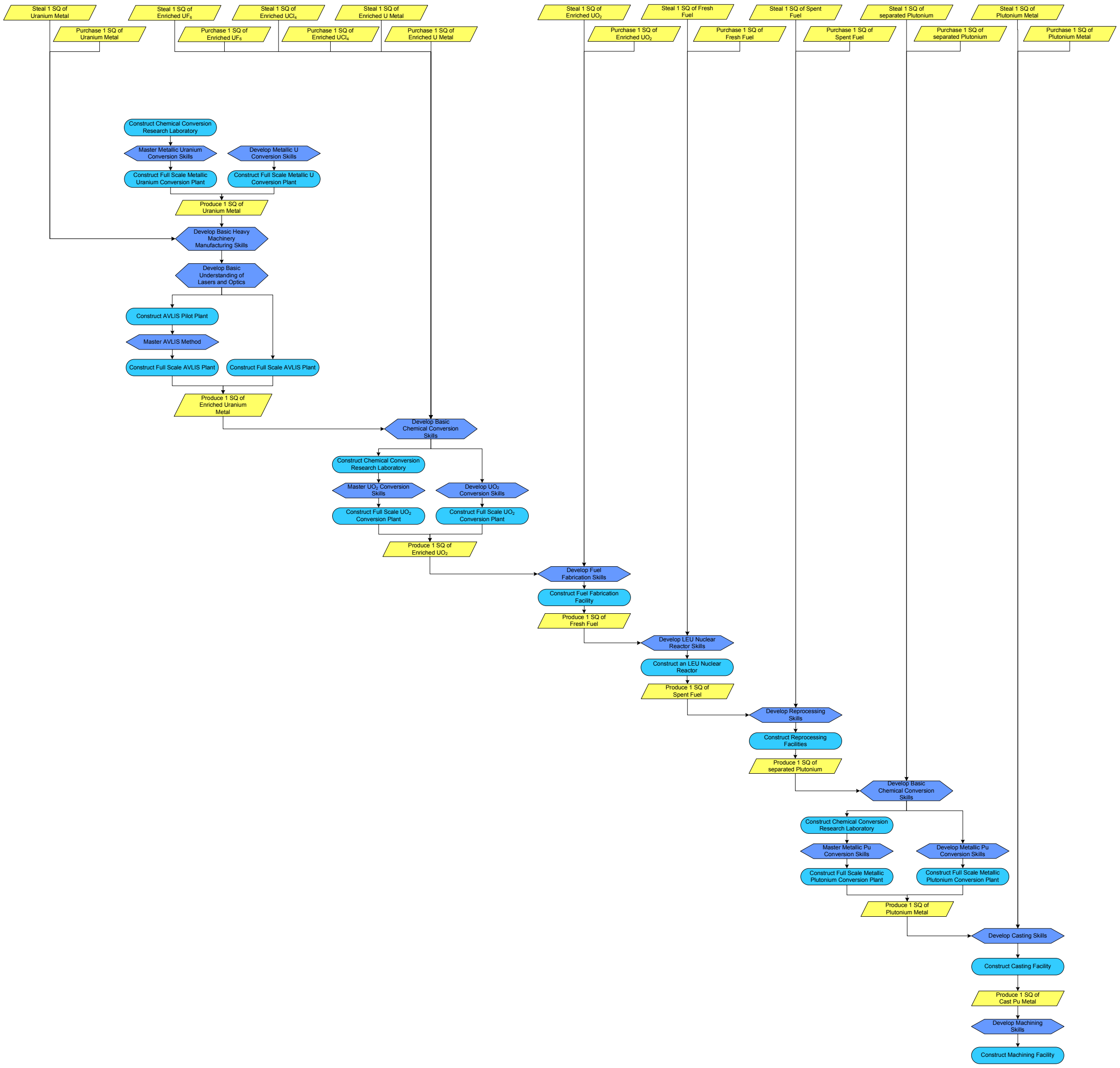


Figure 11. Last section of the Pu (LEU) portion of the network

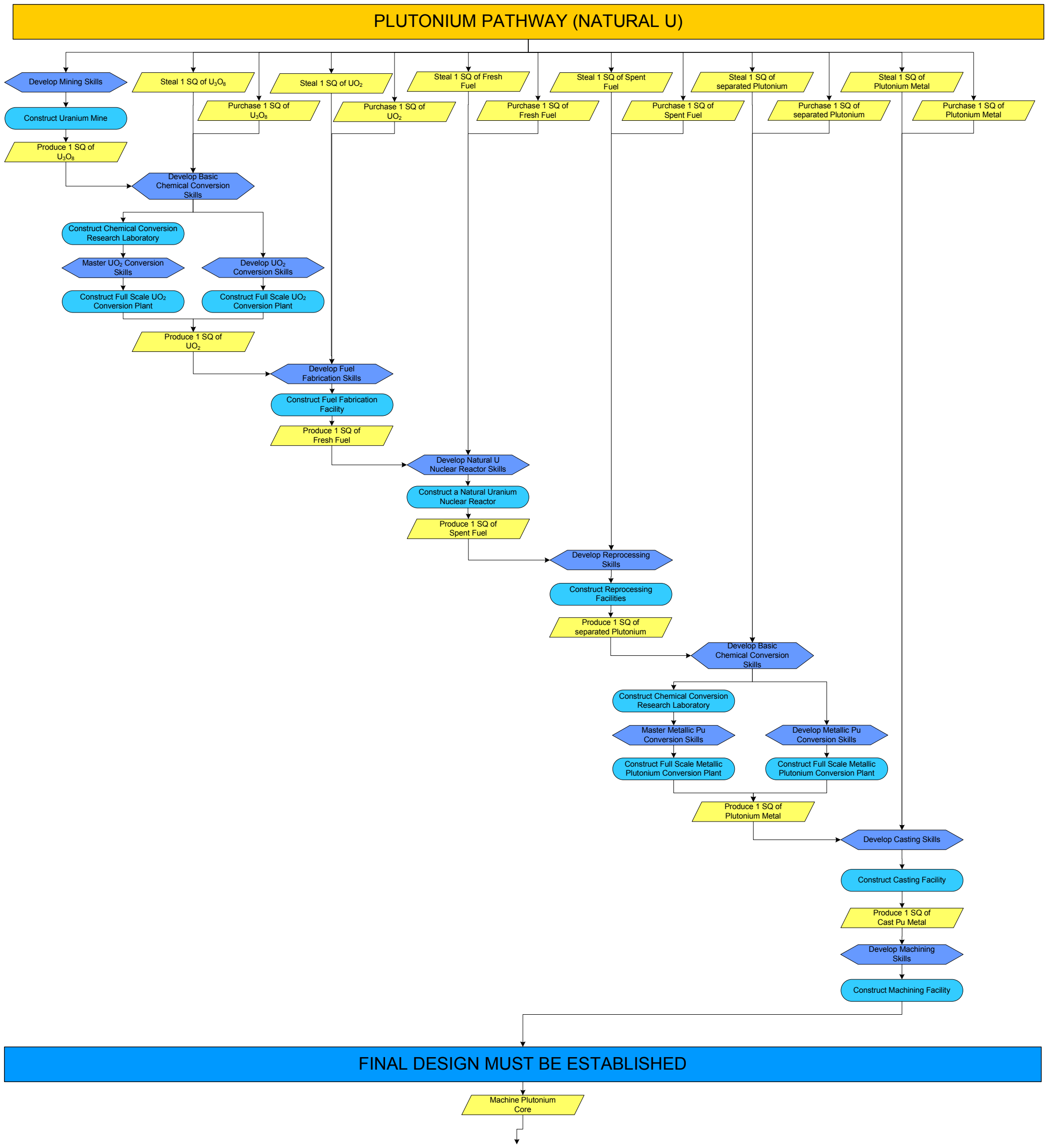


Figure 12. Plutonium section of the network produced via natural uranium

II.B. Assessment of Network

As materials, skills, or facilities are produced, each of these is available for the next step in the pathway. For example, when U_3O_8 is produced at the mine, it can then be processed in future steps until weapons useable material is produced. This could consist of either producing a form of uranium that can be enriched or used in a reactor to produce plutonium

To produce HEU, there are a number of different chemical forms of uranium that can be enriched. The network was developed to include as many of these forms as is feasible (Figure 13). It should be noted however that only the currently deployed forms (either industrial or research) are included.

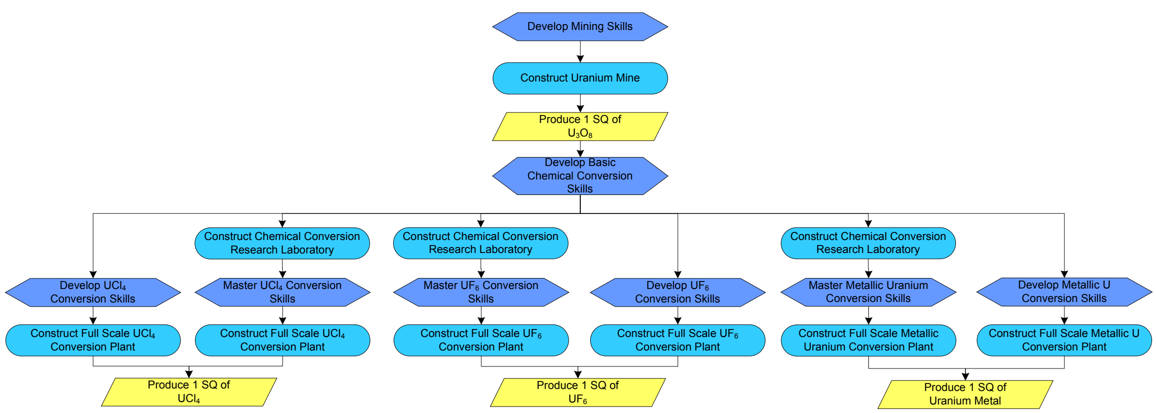


Figure 13. HEU area of the pathways network showing the various chemical forms of uranium that can be enriched

The network also includes paths for purchasing or stealing any materials needed (Figure 14). These routes essentially allow for effectively bypassing entire sections of the network.

It must be noted that even though this network is designed to capture as many pathways as possible to the acquisition of SNM, there are certain scenarios that may not be modeled correctly. For example, the network can not currently model an organization that has already acquired LEU and wishes to further enrich it to HEU. The network currently forces that organization to produce LEU fuel out of it and produce Pu in a reactor. While this scenario is plausible, the way the network is currently designed it would require an entire new section to model this correctly. This type of scenario may be included in future capabilities.

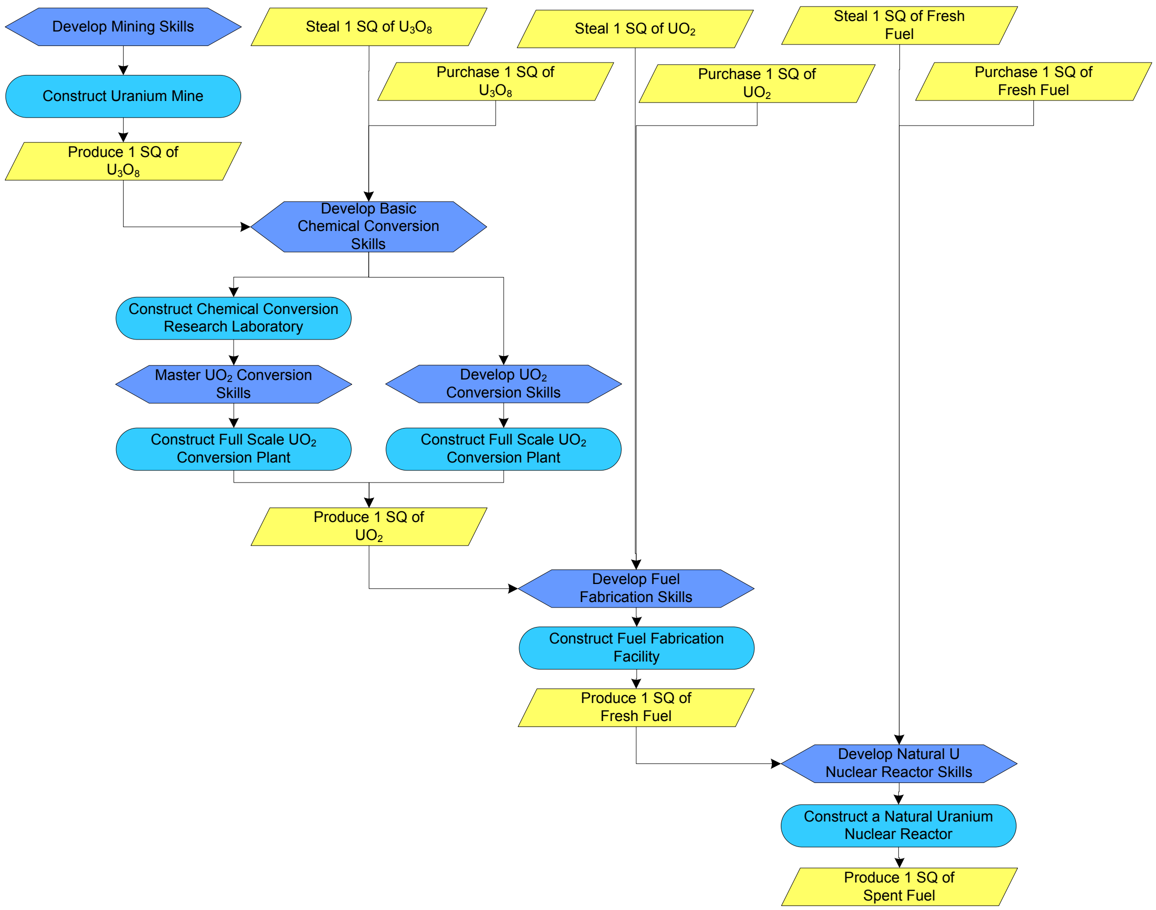


Figure 14. Section of the network showing pathways for purchasing or stealing material.

This network is a material driven system. Because the framework of the system allows for stealing and purchasing material, that enables an organization to skip sections through the acquisition of material. The skill and facility nodes do not enable this type of behavior in the system. This feature of the network is a result of the fact that even with a skill and/or facility towards the end of any of the paths, without the material to process through the path, the organization will still not achieve its goals. Inversely, if the organization is able to acquire material, they may then begin to develop the skills and build the facilities that are required to process that material towards SNM. If the network architecture was different, for example if the facility nodes were to include not only the building of the facility but the production of the material as well, the network and the methodology would have to change accordingly.

It should also be noted that even in the existing framework of the network, acquisition of facilities and skill sets will still drastically effect the choices the organization is likely to make. Each path contains a pre-existing skill or facility will look more attractive to the organization simply by virtue of the fact that it no longer requires all of the resources that would have been needed for the facility or skill they begin the simulation with. While the methodology does not force the organization to choose any path it already has facilities or skills in, it will determine whether or not simply purchasing or stealing material that will feed directly into the skill or facility is the most effective use of the resources available to the organization.

CHAPTER III

NODE DEVELOPMENT

Once the network architecture was established, the characteristics defining the difficulty of achieving any given node were developed. As described in Chapter II, there are three basic types of nodes, however the material nodes must also be broken into the three ways they may be acquired. Thus, the five nodes the user will observe in the network are as follows:

1. Skills
2. Facilities
3. Material produced in a facility
4. Material acquired through theft, and
5. Material purchased on the black market

The difficulty of successfully completing each node depends on the difficulty of the node and the resources available to the organization.

III.A. Resource Types

Each type of node will require a specific set of resource types. However, two nodes of the same type, while requiring the same types of resources will most likely require differing amounts of those resources. For example, a reprocessing facility and enrichment plant will both require construction workers, money, and land but the amount of each required may be drastically different.

The following is a list of all of the resource types used on any of the nodes:

1. Financial**:** Every node in the network has some cost associated with obtaining it. Whether it is the money required to buy materials for a facility, the money used to pay for education to obtain a skill, etc.

2. Available Land**:** This represents the amount of land that facilities can be built on covertly. Every facility has a footprint that is associated with it and any path that requires more land than the organization has available will not be considered.

3. International Networking Capacity**:** This parameter is designed to indicate how many contacts the organization has globally. This parameter is unique because it is the only one that uses a simple 1-10 scale. This the scale is meant to represent how internationally capable the group of interest is. This could reflect their involvement or familiarity with Black Market activities, alliances with other organizations operating in many different countries or regions, etc.

4. Technicians**:** This resource is designed to reflect the number of facility operators/technicians available to the organization. These operators have the equivalent of a high-school or higher education with some experience operating machinery and/or technical systems.

5. Construction Workers**:** This resource categorizes the number of unskilled laborers available for construction projects. It is assumed that all facilities are built and operated covertly.

6. Special Forces**:** This parameter is meant to determine the organizations ability to conduct covert raids on any facility of interest. This resource is solely used in the "Steal Material" nodes.

7. Ph.D. Level Scientists**:** The number of scientists an organization has is designed to illustrate how easily and quickly the organization can develop new skills and put them to use. The model allows for the input of various levels of scientific expertise. The three levels are simply PhD, masters, and bachelors. While these will easily translate into a given level of education, the user must use his/her own judgment when determining how to take informal education and any real world experience into account. It should also be noted that this parameter assumes the organization's scientists are a healthy mix of all applicable fields. The fields of interest could include: nuclear engineering, physics, chemistry, metallurgy, and

civil engineering. These scientists should either have these backgrounds or have the capacity to learn the required skills in a reasonable timeframe.

8. Master Level Scientists: This resource is identical to Ph.D. level scientists in every way except effectiveness. A masters level scientist serves the same purpose as a Ph.D. level scientist, he is just not quite as efficient at performing his job, thus will take more time to complete a task.

9. Bachelor Level Scientists: This resource is identical to Ph.D. and masters level scientists in every way except effectiveness. A bachelor level scientist serves the same purpose as a Ph.D. and master level scientist, he is just not quite as efficient at performing his job, thus will take more time to complete a task.

10. Sustained Capability**:** This parameter accounts for whether or not the organization desires the ability to make more than one weapon. If the organization does desire multiple devices, then more focus will be put on producing material indigenously. On the other hand, if only a small number of weapons is required, then the organization will be more likely to purchase or steal material.

III.B. Resources Used by Each Node Type

With all of the resources defined it is prudent to distinguish which node types make use of the various resource types:

1. Skills: Require the time of scientists and a financial requirement.
2. Facilities: Require the time of construction workers and a financial requirement.
3. Material produced indigenously: Requires the time of operators/technicians and scientists along with a financial requirement.
4. Material purchased on the black market: Requires a degree of international networking capabilities and a has a financial requirement.
5. Material stolen: Requires a degree of international networking capabilities, the ability to perform special forces operations, and has a financial requirement.

III.C. Detailed Node Descriptions by Node Type

This section provides a detailed description of each node in Figure 3.

III.C.1.Skills

The following list provides a description of all of the skill-type nodes:

1. Mining: As basic as this skill sounds and as prevalent as it is around the world, it is still required in order to obtain the most basic or sources for uranium, ore from a uranium mine. Although this skill may be (relatively) easy to obtain, it will still require resources to accomplish.
2. Basic Chemical Conversion: This skill is meant to capture the reality that no chemical engineer would be able to develop the knowledge necessary for the more unique chemical processes in the network without first acquainting themselves with basic chemical engineering skills.
3. Metallic Plutonium Conversion: This skill is designed to account for the expertise that must be obtained in order for the organization to convert any plutonium source they obtain into plutonium metal suitable for being cast into a weapon pit.
4. Metallic Uranium Conversion: Similar to the previous skill, this is designed to capture the expertise required for converting any source of uranium that the organization is able to obtain into metallic uranium capable of being cast into a weapon pit

5. Uranium Hexafluoride Conversion: This skill represents the training that must be obtained in converting feed material into UF6 that will be used in various enrichment techniques.

6. Uranium Dioxide Conversion: This skill is simply another chemical processing skill that must be obtained in order to convert feed material in UO2 in order to feed into the next process, usually the manufacturing of fresh nuclear reactor fuel.

7. Uranium Tetrachloride Conversion: In order to enrich uranium using the electromagnetic isotope separation method (EMIS) an organization will have to

use UCl4 as feed for the system, thus any source of uranium the organization has access to must be converted into UCl4 in order to be enriched using this method.

8. Heavy Machinery Manufacturing: In order for an organization to be capable of indigenously constructing any of the more complex facilities in the network they must have a fairly robust industrial base to draw on. Much of the equipment and infrastructure that goes into many nuclear facilities can not be made in the majority of countries in the world, so access to such capacity is vital.

9. Accelerator Physics: This skill is a prerequisite for the electromagnetic isotope separation enrichment process. Before the skills can be acquired to construct or operate an EMIS system, an organization must understand the basics of how such a system would function, this skill set captures this.

10. Micro Porous Barriers: The construction and operation of a gaseous diffusion enrichment plant involves the management of the micro porous barriers contained in the machinery. The organization must have the ability to understand these systems before they can manage such a large scale endeavor.

11. High Speed Machinery: The equipment associated with a gas centrifuge enrichment plant is designed to operate at very high RPMs. This material must be specially constructed for this job and requires detailed knowledge of how such operations must be performed and maintained. The basics of these processes must be known before such complex arrangements may be operated.

12. Lasers and Optics: There are two theoretical enrichment processes that may use such skill sets. Atomic vapor laser isotope separation(AVLIS) and molecular laser isotope enrichment (MLIS) both use a highly tuned laser to excite only the uranium 235 atoms in a feed stream to enrich material. Neither of these processes have ever been demonstrated successfully outside of a laboratory, however, they are both theoretically ultra efficient, thus very attractive to a potential proliferators. However, in order to develop the requisite skills to attempt enrichment is such a way an organization

13. Aerosol Dynamics: Jet nozzle enrichment uses properties of high flow gasses to enrich a uranium stream. In order to successfully run such a process, an organization would first have to familiarize with Aerosol Dynamics.

14. Electro Magnetic Isotope Seperation (EMIS): Before an organization could begin to use the EMIS system to enrich uranium they must first be intimately familiar with how these systems operate. While such information specific to this properly may not be taught in western schools, the process is similar to accelerator systems.

15. Gaseous Diffusion: This method of enrichment uses a micro porous barrier to preferentially pass U-235 atoms through a system, thus enriching the stream. Such systems have only been built by weapon states and require large amounts of equipment and electricity to operate. However, these systems were the workhouse of the U.S. and Soviet weapons programs for the purposes of producing Highly Enriched uranium.

16. Gas Centrifuge: This skill set is designed to model the knowledge that must be obtained in order to construct and operate a gas centrifuge enrichment plant.

17. Molecular Laser Isotope Separation (MLIS): This skill is designed to capture the resources that must be spent to obtain the knowledge required to build and operate an MLIS facility.

18. Atomic Vapor Laser Isotope Separation (AVLIS): This is intended to model the difficulties inherent in obtaining the knowledge and skills needed to construct and operate and AVLIS plant

19. Jet Nozzle: This skill set is designed to account for the resources that must be spent on developing the knowledge and skill necessary to construct and operate a Jet Nozzle enrichment plant

20. Fuel Fabrication: The fabrication of fuel to power a covert nuclear reactor intended for weapons material production is a process that requires detailed

knowledge of how to design a core with the correct properties for efficient production and safety.

21. Low Enriched Uranium Reactor: The ability to construct and operate a reactor using low enriched uranium as fuel can be necessary to produce plutonium in many scenarios.

22. Natural Uranium Reactor: Similar to the skill above, this is designed to capture the resources required to build and operate a nuclear reactor using natural uranium as fuel.

23. Spent Fuel Reprocessing: This skill is designed to model the resources required to acquire the requisite knowledge for building and operating a spent fuel reprocessing facility.

24. Casting: Once the SNM is produced, it must be cast into a mold suitable for machining into a weapons pit. The skills required to cast such material are very specialized, and this is meant to capture the resources required to obtain such unique knowledge.

25. Machining: Once the SNM is cast, it must be machined into a core suitable for being placed in a weapon. The skills required to machine such material are very specialized, and this is meant to capture the resources required to obtain such unique knowledge.

III.C.2. Facilities

The following list describes each of the facility-type nodes:

1. Mining: All weapons material begins as uranium in the ground. Mines must be constructed in order to extract ore of a suitable uranium quality.

2. Conversion Facilities: There are many different types of conversion facilities that may be constructed by an organization traversing the network. All require the handling of nuclear material, however some processes are much more difficult

than others. Some deal with Highly Enriched uranium (HEU) or plutonium, very valuable material that must be converted as efficiently as possible. The resources that are required to build these different conversion facilities may be similar, but they will all be unique.

3. Gaseous Diffusion: This facility is expected to model the resources that must be spent on building a gaseous diffusion enrichment plant.

4. Gas Centrifuge: While the most used enrichment process in the world today, the construction of such a facility is still a very complex undertaking. The resources required to construct such a facility will be captured in this node.

5. Jet Nozzle: Few countries have built such facilities because of efficiency issues, however if an organization could obtain the skills required to do so they may find it to be their best option (some speculate this is why the South Africans went this route, obtaining the skill set from a German corporation). The resources required to build such a plant are modeled in this node.

6. EMIS: Constructing such a plant was thought to be so absurd that the U.S. declassified the process after WWII only to find that the Iraqi weapons program intended to use this method after the first gulf war.

7. AVLIS: The resources required to construct an AVLIS plant will be difficult to estimate because the process is only a theoretical one at this point.

8. MLIS: Very similar to the AVLIS process. Such a plant has also never been constructed, and the resources to do so are expected to be large.

9. Fuel Fabrication: This facility is designed to capture the resources required for it to be built. Fuel Fabrication is necessary for both LEU and Nat U reactors to produce plutonium

10. Low Enriched Uranium and Natural Uranium Reactors: One of these facilities will be required to produce plutonium for a weapons program, if that is the path chosen. The resources required to construct such facilities will be captured within

11. Reprocessing: This facility will be required if the organization has a source of spent fuel containing enough plutonium for a weapon. The resources required will be contained within.

12. Machining: Once the SNM has been produced it must be machined into a pit that can be placed into a weapon. This facility will not be difficult to construct (relatively speaking) but is vital to the final steps in weapon production.

III.C.3.Materials

The following list provides a description of each of the material-type nodes:

1. U_3O_8: This material is produced at a uranium Mine.

2. UCl_4: This material is used as feed for the EMIS enrichment process.

3. UF_6: This material is used as feed for many enrichment processes (all of the processes used commercially today).

4. Uranium Metal: This material is used as feed for the AVLIS enrichment process.

5. Low Enriched UF_6: This material is created by many enrichment processes and would be converted to UO2 and used to create fuel for a LEU reactor.

6. Low Enriched UCl_4: This material is created in EMIS enrichment plants and would be converted to UO2 and used to create fuel for a LEU reactor.

7. Low Enriched UO_2: This material is used as feed for a fuel fabrication plant.

8. Low Enriched Uranium Metal: This material is produced from an AVLIS enrichment plant would be converted to UO2 and used to create fuel for a LEU reactor.

9. High Enriched UF_6: This material is produced in many enrichment facilities and would be converted directly to uranium Metal for use in a weapon.

10. High Enriched UCl_4: This material is produced in a EMIS enrichment facility and would be converted directly to uranium Metal for use in a weapon.

11. High Enriched Uranium Metal: This material is produced in a AVLIS enrichment facility and would be used directly in a weapon.

12. Fresh Fuel: This material would be created at a Fuel Fabrication plant and would be used in a nuclear reactor to produce spent fuel (which contains plutonium).

13. Spent Fuel: This material would be produced in a reactor but would have to be reprocessed to extract plutonium for use in a weapon.

14. Separated Plutonium: This material is produced at a reprocessing plant and would be converted to plutonium metal for use in a nuclear weapon.

15. Plutonium Metal: This material is produced at a conversion plant and used directly in a nuclear weapon.

It should be noted that each of these materials can be acquired through production, theft, or purchase; however, the resources required vary depending on the means of acquisition.

CHAPTER IV

DESCRIPTION OF THE NUCLEAR MATERIALS ACQUISITION PATHWAYS ANALYSIS

This chapter describes the mathematical model used in determining how the organization will traverse the network. This analysis begins by determining which paths are available to the organization. The network shown in Figure 3 has 646 unique paths. Each of the individual nodes within the network must then be given a probability of being chosen based on all of the resources it requires and the resources available to the organization being simulated. The probabilities must then be compiled into a likelihood for each of the paths. These likelihoods will determine which paths are most attractive to the organization. Using a random number generator, a series of paths is chosen to be simulated to determine the organizations rate of success for acquiring SNM. The organizations rate of success along these paths will be determined based on a resource evaluation incorporating learning curves.

IV.A. Building the Paths Matrix

Section III.A shows the 10 resource types considered here. The organization to be analyzed is defined by its resources as well as any existing material, skills, and facilities. Assume that for each resource type j the organization begins the simulation with some quantity of that resource x_j.

The network is defined by i=1,…, I nodes. All of the paths in the network can be linearized into a finite (though large) set of possible paths. The organization of these linearized paths can be assembled into a matrix where each column represents a path and the first node for that path occupies the first row, the second node in the second row, etc.

IV.B. Expected Probabilities of Success for Each Node

Before an organization begins to try to develop SNM that organization will assess which pathway it believes will have the highest probability of success. That assessment will be based on the difficulty of each node with respect to the organization’s resources.

The probability ($P_{i,j}$) that the organization will expect to successfully complete node *i* based on resource x_j is given by:

$$P_{i,j} = \frac{\exp(\alpha_{i,j} x_j) - 1}{\exp(\alpha_{i,j} x_{j\max}) - 1} \tag{4.1}$$

where $\alpha_{i,j}$ is a constant, and $x_{j,max}$ is the maximum amount of resource *j* allowed. x_j is determined from the organization definition and $x_{j,max}$ is determined through empirical evidence. $\alpha_{i,j}$ is a constant which will be learned through expert opinion. A plot of $P_{i,j}$ for various values of $\alpha_{i,j}$ is shown in Figure 15. This functional form was chosen because it reflects the expectations of the proliferator. In some cases, the probability of success on a node is extremely low unless the organization's resources are above a certain value (for example, when $\alpha = -1.0$). However, in most cases, we expect the probability of success to be essentially linear with respect to the quantity of resource available.

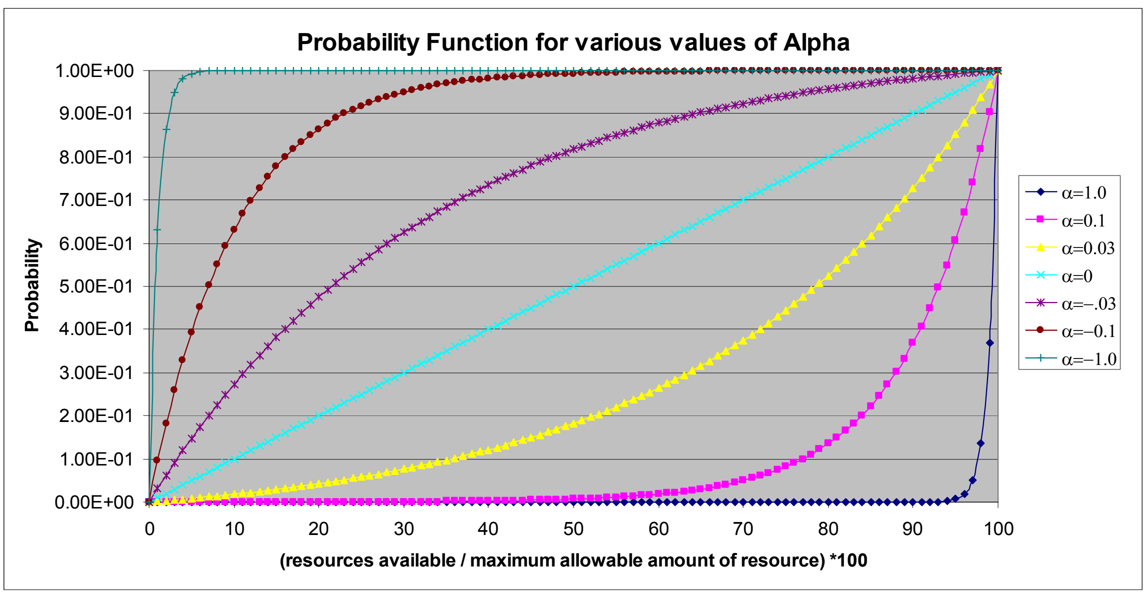


Figure 15. Probability function for various values of alpha

The organization's expected probability of success on node *i* considering all resources used on that node is given by:

$$N_i = \prod_j P_{i,j} \tag{4.2}$$

For example, the "Produce 1 SQ of UCl_4" node uses the following resources: financial, technicians, and scientists. If for this node (i) the probabilities for each of the resources was given by:

$$P_{i,finance} = 0.866$$
$$P_{i,technician} = 0.418$$
$$P_{i,scientist} = 0.328$$

then the expected probability of success on node i is given by:

$$N_i = 0.866 * 0.418 * .0328 = \boxed{0.119}$$

Additionally, each path K has an expected probability of success (L_k) equal to the product of the expected probabilities for each node along the path or:

$$L_k = \prod_i N_i \tag{4.3}$$

Substituting eqs. (4.1) and (4.2) into eq (4.3) yields:

$$L_k = \prod_i \prod_j P_{i,j} \tag{4.4}$$

for all values of i and j along path k. Note that if $P_{i,j} = 0$ for any value of (i,j) along path k then the expected probability of success on that path would be equal to zero. This matches our intuition of how an organization would assess its likelihood of success.

IV.C. Choosing the Paths

The probabilities derived above will be used to determine the most likely path for the organization to attempt. This effectively consists of the organization forecasting what it expects to be the best path to follow. The actual chance of success on any path will be calculated in the following section. To simplify this process, a normalized likelihood is calculated as follows:

$$\tilde{L}_k = L_k \Big/ \sum_k L_k \tag{4.5}$$

Thus, $\sum_k \tilde{L}_k = 1$

Since the values of $\tilde{L}_k$ are between zero and one, the paths can be chosen using a random number generator. A random number (δ) is determined and the path (Λ) chosen to attempt is the path such that:

$$\delta > \sum_{K=1}^{\Lambda-1} \tilde{L}_k \quad and \quad \delta < \sum_{K=1}^{\Lambda} \tilde{L}_k \tag{4.6}$$

This process can be repeated many times to sample a distribution of paths based on these expected probabilities of success. This distribution will then be used in the simulations that follow on determining if these paths in fact can be successfully accomplished without the adversary being interrupted or caught.

IV.D. Determining the Success Rate of the Attempted Paths

We wish to know how the organization will go about trying to complete the paths, how far we expect the organization to proceed down each path, and what the probability of success for the organization to achieve each path is. This simulation makes use of standard learning curve theory[22,23].

Each node requires a certain type and quantity of resources to complete. The organization has available a certain type and quantity of resources. As the organization attempts to complete a node, it will expend resources and time. The organization can expend more resources and accomplish a node in a short period of time or less resources and accomplish a node in a longer period of time. Also, while attempting to complete any given node there is a probability per unit time that the organization will get caught or will fail catastrophically. The default time step used in this simulation is 1 week.

In this learning theory model each node i requires a certain number of units (u_i) to complete. Each time step (γ) the organization will produce some quantity of units ($Y_{i,\gamma,j}$) from resource j. The number of units produced for each time step depends on the quantity of resource available and the number of time steps already spent attempting the task. The number of units produced for the step γ is given by:

$$Y_{i,\gamma,j} = \frac{x_j}{C_{i,\gamma,j}} \tag{4.7}$$

where $C_{i,\gamma,j}$ is the cost of producing a unit for node *i* at the step γ from resource *j*. The cost per unit is determined using a standard learning curve model[22,23]:

$$C_{i,\gamma,j} = C_{i,1,j} * (\gamma + c)^{\ln(S)/\ln(2)} \tag{4.8}$$

where $C_{i,1,j}$ is the cost of the first unit, *c* is the number of units the organization has already produced prior to the simulation (effectively practice units), and *S* is the fraction by which cost decreases when time doubles. An example learning curve is shown in Figure 16.

Thus, the number of time steps required to complete the node is determined when $u_i < \sum_{\gamma} Y_{i,\gamma,j}$ for all resources, *j*. Since each node requires multiple resources, an additional constraint is added in which the organization can only produce as many units per time step as their most limiting resource allows. Each resource does not have a certain number of units it must produce, they all must work together to meet the same unit requirement simultaneously. For example, using eq. (4.7) we can determine how many units the organization can produce using just their operators, their scientists, and their budget. Of these, whichever number is the smallest is the number of units produced that time step. This ensures that even if an organization has an enormous budget, they will not succeed without recruiting a sufficient amount of other resources as well (in this case, scientists and facility operators/technicians).

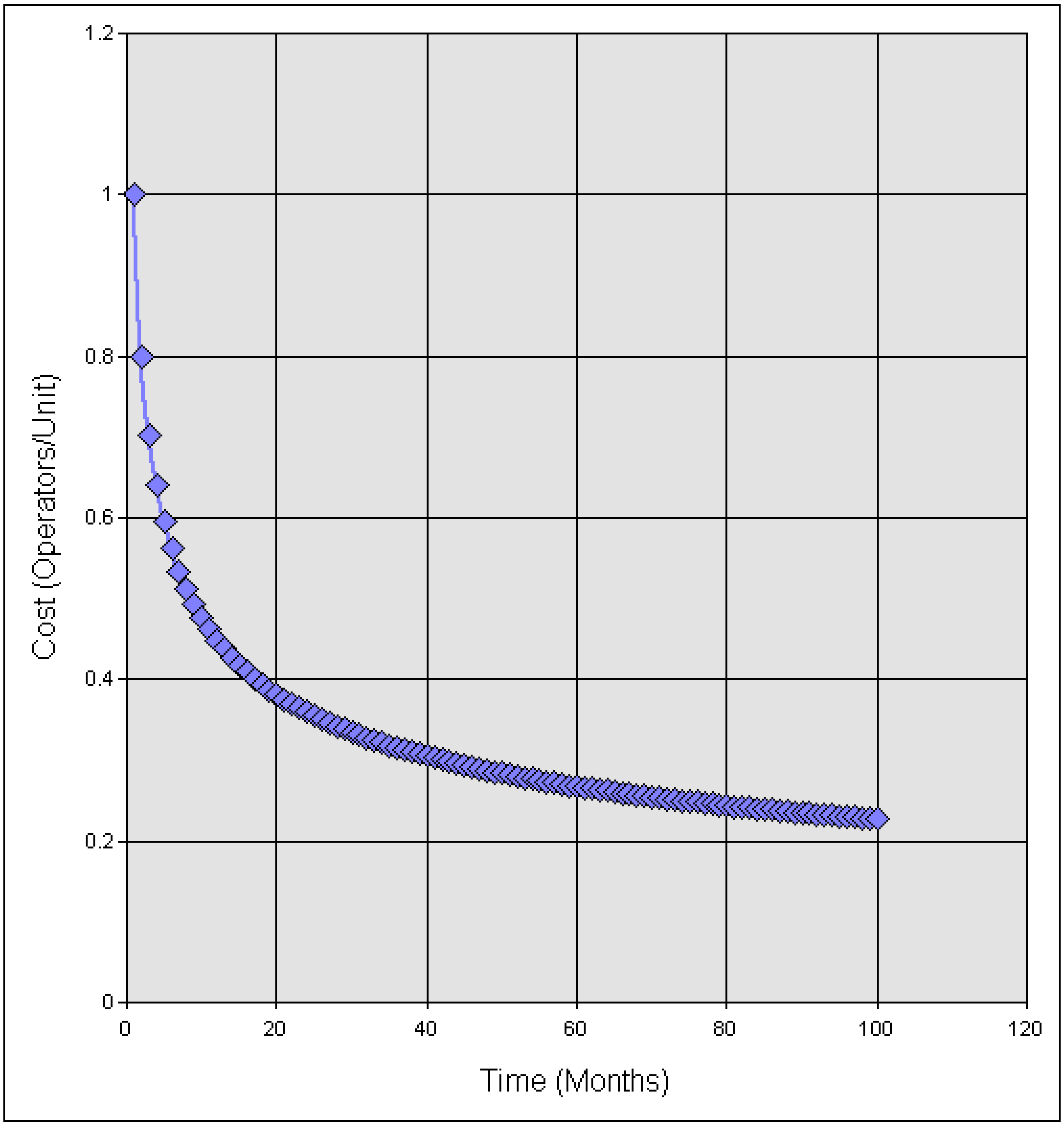


Figure 16. Learning curve showing the decrease in unit cost with increased task time for the operator resource

An example follows. Producing any material requires operators, scientists, and money. Assume the cost of the first unit equals 1 unit per operator, 1 unit per scientist, and 1 unit per 10,000 dollars. The fraction by which cost decreases is different for all three resources, and no units were produced in training. Let us further assume the organization has access to 20 operators, 7 scientists and 100,000 dollars. This means that, for the first month:

$$20\text{ operators}\left(\frac{1\text{ unit}}{\text{operators}}\right) = 20\text{ units}$$

$$7\text{ scientists}\left(\frac{1\text{ unit}}{\text{scientist}}\right) = 7\text{ units}$$

$$100{,}000\text{ dollars}\left(\frac{1\text{ unit}}{10{,}000\text{ dollars}}\right) = 10\text{ units}$$

Since the number of scientists is the limiting resource, it will determine how many units the organization can complete in the first attempt to produce the material. Thus, in the first time step 7 units will be produced. If the financial cost per unit is constant, the cost for scientists decrease by a factor of 0.6, and the cost for operators decreases by a factor of 0.8, then:

$$20\text{ operators}\left(\frac{1\text{ unit}}{0.8 * \text{operators}}\right) = 25\text{ units}$$

$$7\text{ scientists}\left(\frac{1\text{ unit}}{0.6 * \text{scientist}}\right) = 11.66\text{ units}$$

$$100{,}000\text{ dollars}\left(\frac{1\text{ unit}}{1.0 * 10{,}000\text{ dollars}}\right) = 10\text{ units}$$

The limiting resource for this step has changed as a result of the learning curve associated with the scientists. Thus, in the second time step 10 units are produce. So, for the first month 7 units were produced, the second month saw 10 units completed, if we assume that the node requires 20 units for completion then it will be complete in 3 weeks with the resources available. However, since there is a probability of detection or catastrophic failure every time step there is a chance that the organization will fail to complete the node.

This process will continue for every node along every path that was chosen to be analyzed, until the organization either fails on a path or successfully completes it.

CHAPTER V

IMPLEMENTATION

V.A. User Input

The network was built in Microsoft Visio. The macro system that Visio employs uses Visual Basic for Applications (VBA). Thus VBA is already ingrained in the network architecture, making it the logical language of choice for the analysis coding.

When the user launches the Visio File containing the network, the code prompts the user to enter any relevant information on the organization. This provides the definition for the organization. This initial form (Figure 17, Figure 18, and Figure 19) obtains the organization description. The first three tabs (skills, facilities, and materials) provide the user the ability to define any nodes already obtained by the organization. The skills tab is shown in Figure 17, and facilities and materials tabs are shown in Figure 18. This will allow the organization to do three things. First, if any of the previously acquired nodes are a material, then it is assumed the organization must begin with that material. In that case, every path the model considers will begin with that material. Second, if one of the nodes is not a material, the organization will be able to skip either the skill or facility associated with the pre-existing, non-material parameter. Third, the model will automatically weight the paths that contain the pre-existing parameters such that the organization is more likely to choose a path that utilizes them. The manner in which this is done is described in Chapter IV.

The fourth tab in Figure 19 gives the user the option of stressing plutonium production versus HEU production. The code accomplishes this by weighting all of the appropriate paths. This weighting is described in Chapter IV. The fifth tab shown in Figure 19 defines the resource available to the organization.

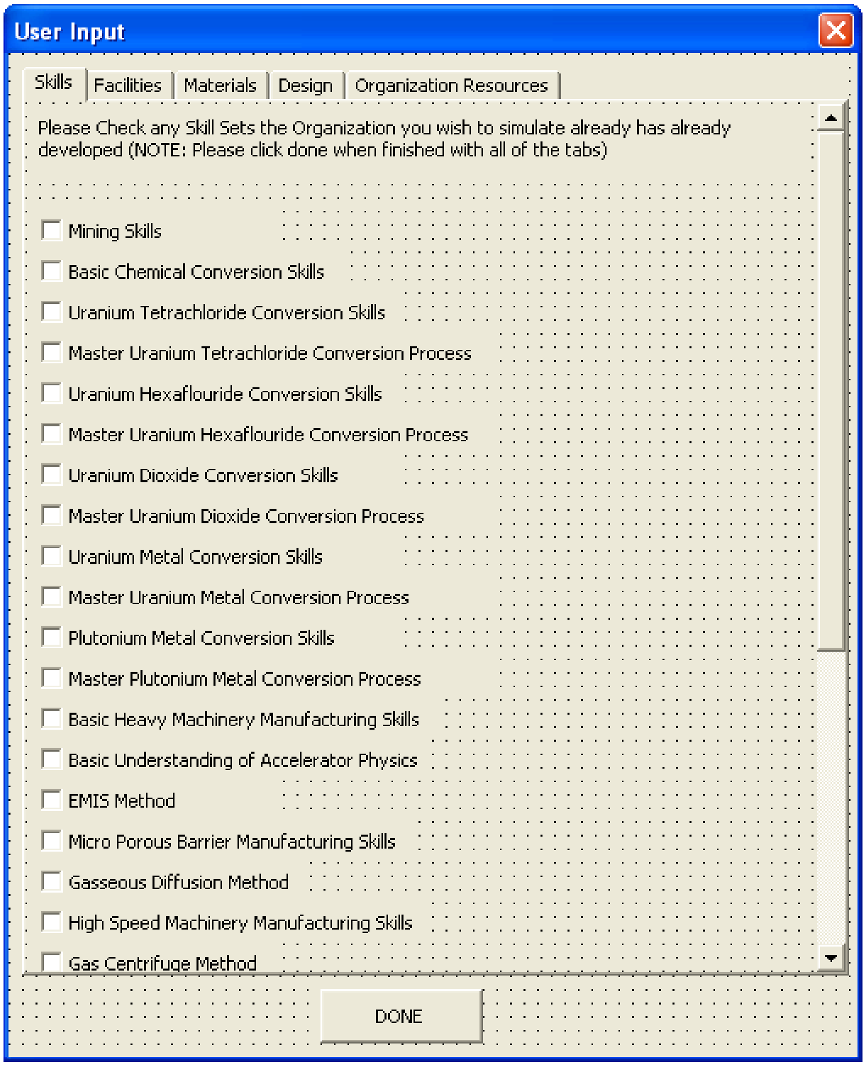


Figure 17. This figure and the following four show the different tabs of the same form the user will see when the program is launched. This is the skills tab.

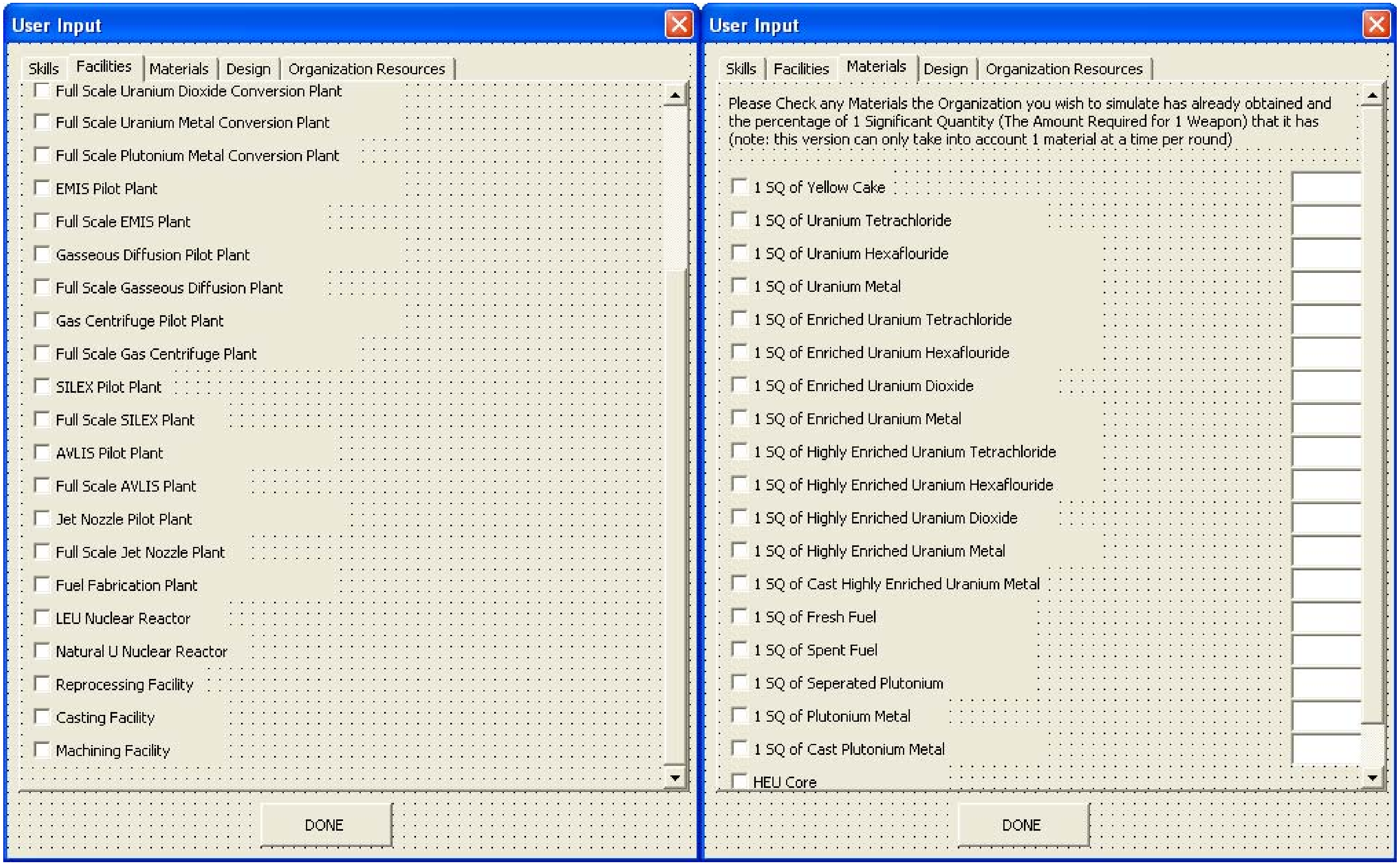


Figure 18. The facilities and materials tabs

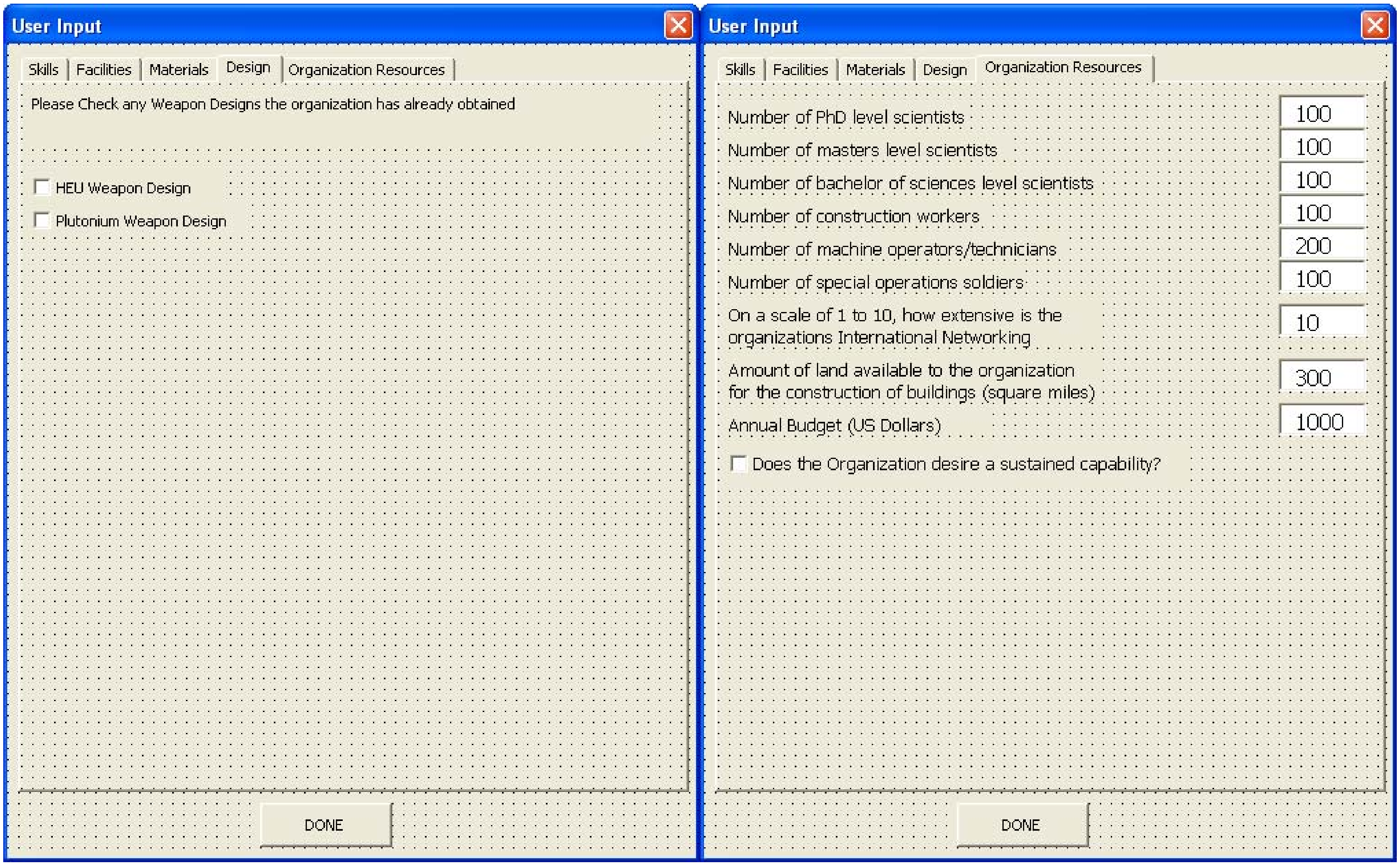


Figure 19. The design and resources tabs

Once the organization is defined, the code will prompt the user for the number of rounds to be simulated. The number of rounds is the number of times the code will "roll the die" to determine which path the organization chooses to attempt. This number directly effects how long the code will take to run, ranging from a few minutes to several days.

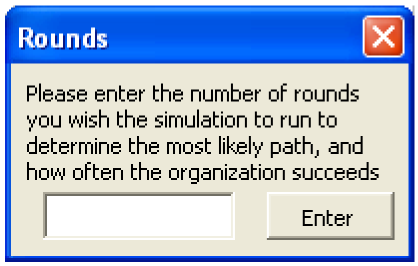


Figure 20. The Form for entering the number of rounds

V.B. Node Adjustments

Once the organization definition is completed and the number of rounds entered, the user will be able to alter any of the node characteristics prior to execution of the analysis. By double clicking any node of the network, the user will have access to all of the information contained in that node. Thus, the user can change the values of every node if desired. A default set of node characteristics was calculated based on expert opinion and input to the network. However, this feature provides the analyst the ability to modify this data as appropriate.

The user is allowed to directly vary x and x_{max} through the form displayed in Figure 21, and may indirectly vary α by adjusting where the organization is likely to find the node 50% acceptable based on the resource of interest. The code solves for alpha using a simple iteration method, as alpha cannot be solved for directly. Figure 21 shows the value of this probability function for various values of α where x ranges from 1% to 100% of x_{max}.

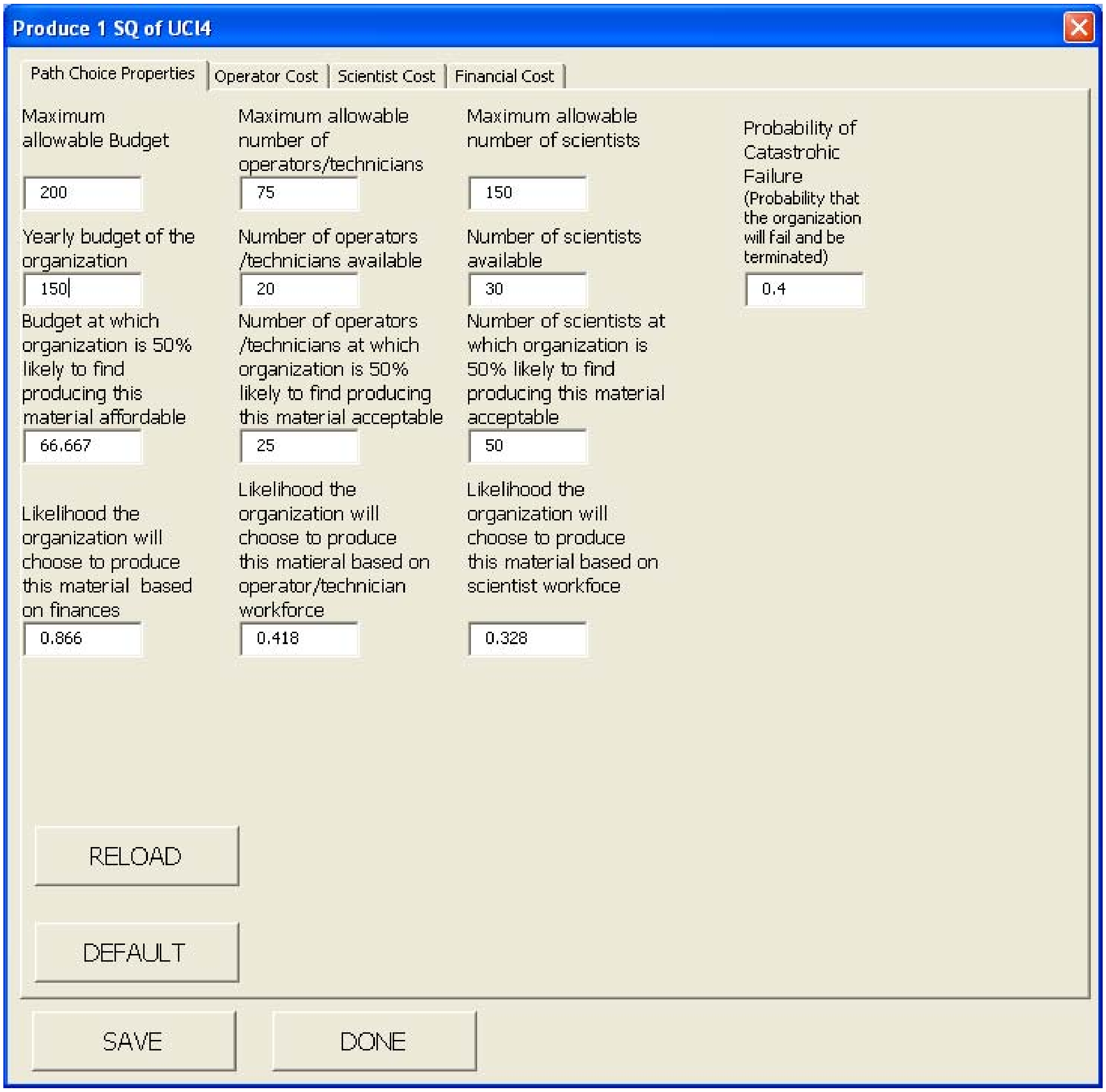


Figure 21. Probabilities associated with a material production node

Using Visio the characteristics of each node can be viewed through an Excel-style spreadsheet (an example is shown in Figure 22). This spreadsheet typically exists to store general Visio information such as position, title, color, and shape; however, additional sections were added to these shapes to store the node characteristics. Each piece of information stored in this spreadsheet also has a unique address that can be accessed by VBA and the code.

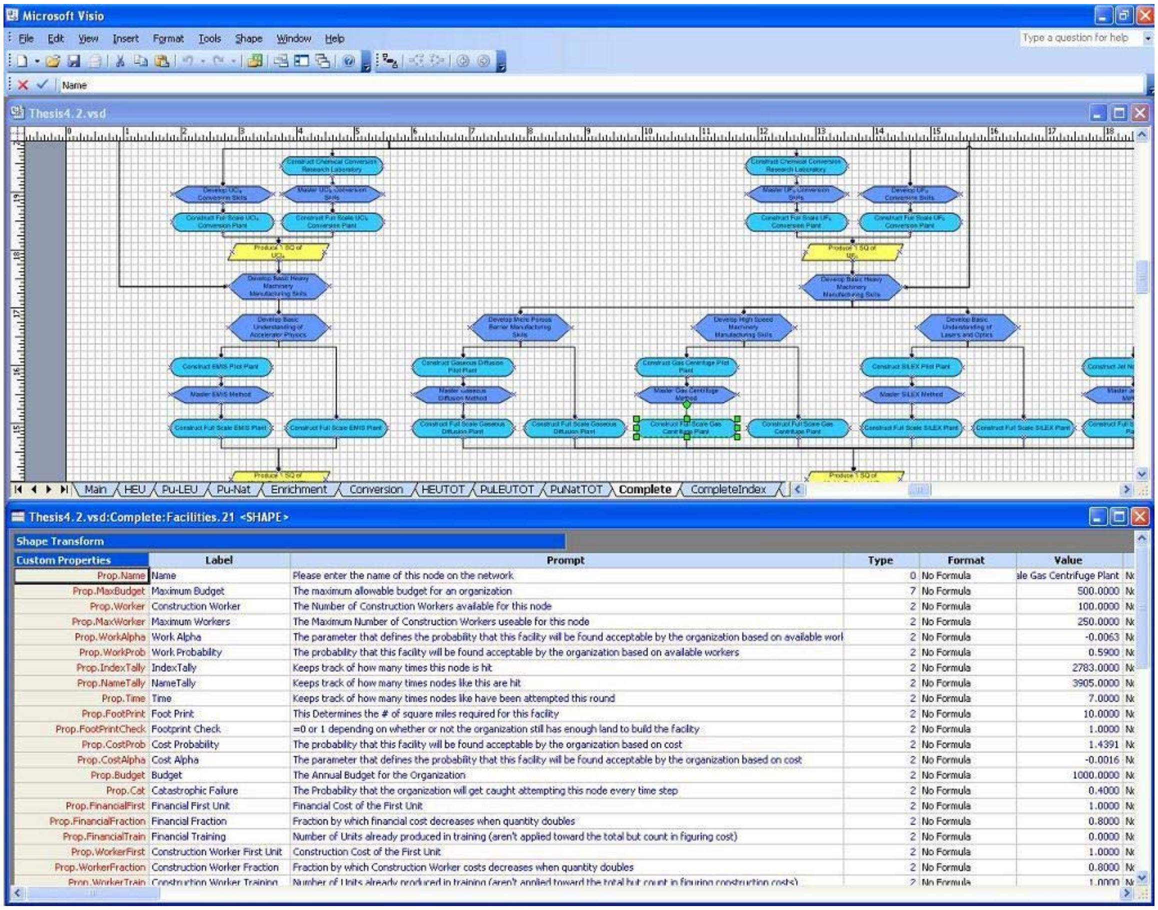


Figure 22. Spreadsheet associated with a facility node as seen within Visio

A simple form will be present while the User is editing node properties (Figure 23). When the user has completed browsing and/or altering the network they can signal the program to begin the analysis by clicking the “Run” button. The code will then execute the analysis described in Chapter IV.

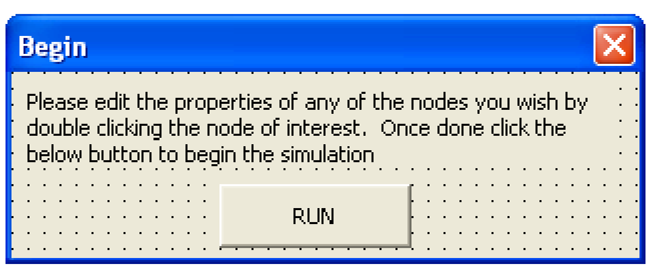


Figure 23. For executing the analysis.

Once the code has run its course as specified by the user it will generate all of the data relevant to the simulation. This data will be presented to the user in a standard Visio form in addition to being saved as various text files for future reference. Some of the data saved to these text files includes the paths most often chosen by the organization and their rate of success, all of the paths available to the organization, the nodes most often attempted by the organization, and the result of every round the user instructed the code to run.

CHAPTER VI

RESULTS

The results generated from running the code on a few simple scenarios show the user what should be expected. Scenarios in which an organization is tasked to complete the network with the minimal resources available to many organizations result in failure 100% of the time. Even with a moderate amount of help from perhaps a friendly nation state is not enough for such an organization to be successful at such a large undertaking. It takes considerable access to a modern industrial base and pre-existing facilities in order for such an organization to be successful even 1% of the time in the simulations run here.

VI.A. Example 1: Small Organization with Limited Resources

This example problem considered a small, sub-state organization that has already obtained UF_6 and wishes to enrich it to make an HEU weapon. This example was simulated to demonstrate the output as well as the test the code's ability to properly choose paths when the logical result is intuitive.

If we refer to Figure 7 we can see the various ways in which UF6 can be enriched to produce HEU. In this example, the choice of enrichment techniques is the only choice available to the organization, all other steps are intuitive.

The resources available to the organization are as follows:

- 1 PhD level scientist
- 1 Masters level scientist
- 1 bachelor of science level scientist
- 50 construction workers
- 5 machine operators/technicians
- 1 team of special operations soldiers (although it will not be used anywhere in the simulation)
- Rank 10 of international networking
- 10 square miles of land
- Annual budget of 10 million U.S. dollars
- 1 SQ of Uranium Hexafluoride

- HEU Weapon Design

This simulation used the default node values developed through expert elicitation mentioned earlier. The results from this simulation are displayed in Figure 24 and Figure 25. These screens show a summary of the results from the simulation.

The simulation also generated 8 text files that contain the history of all of the simulations. These files can be analyzed by the user external to the code if additional details are desired.

Figure 24 shows the most likely path the organization will take. In this case, with such meager resources (most of which was money) the jet nozzle method of enrichment was chosen as most likely. This was the expected result because this particular method does not require a prerequisite skill set, nor does it require large, expensive facilities.

The gas centrifuge enrichment method was predicted to occur 20% of the time. This is not especially surprising as all of the modern enrichment facilities being built around the world are of this design. While this design is certainly the most efficient of the proven technologies, it is still relatively complicated to achieve when compared to the Jet Nozzle method.

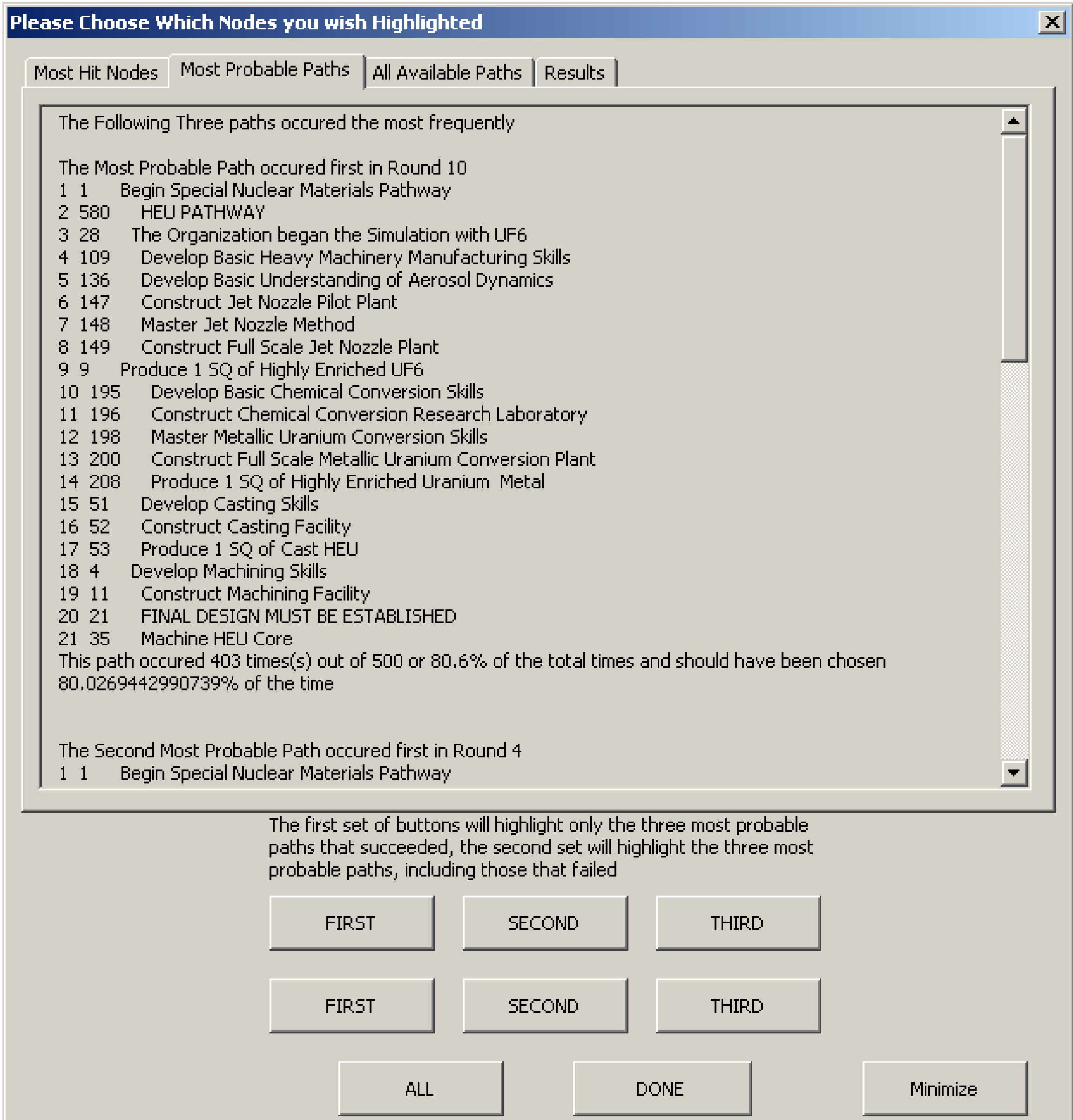


Figure 24. Output screen from example 1

Figure 26 shows the results of this path analysis. The organization chose the jet nozzle path most often but failed at it every time. It should be noted that the nodes hit the most often were those involved with obtaining the initial material (this was included even though the organization began the simulation with it to stress how important that initial step is), developing the basic industrial capacity to even begin such an undertaking, and the first skill set that the organization must acquire.

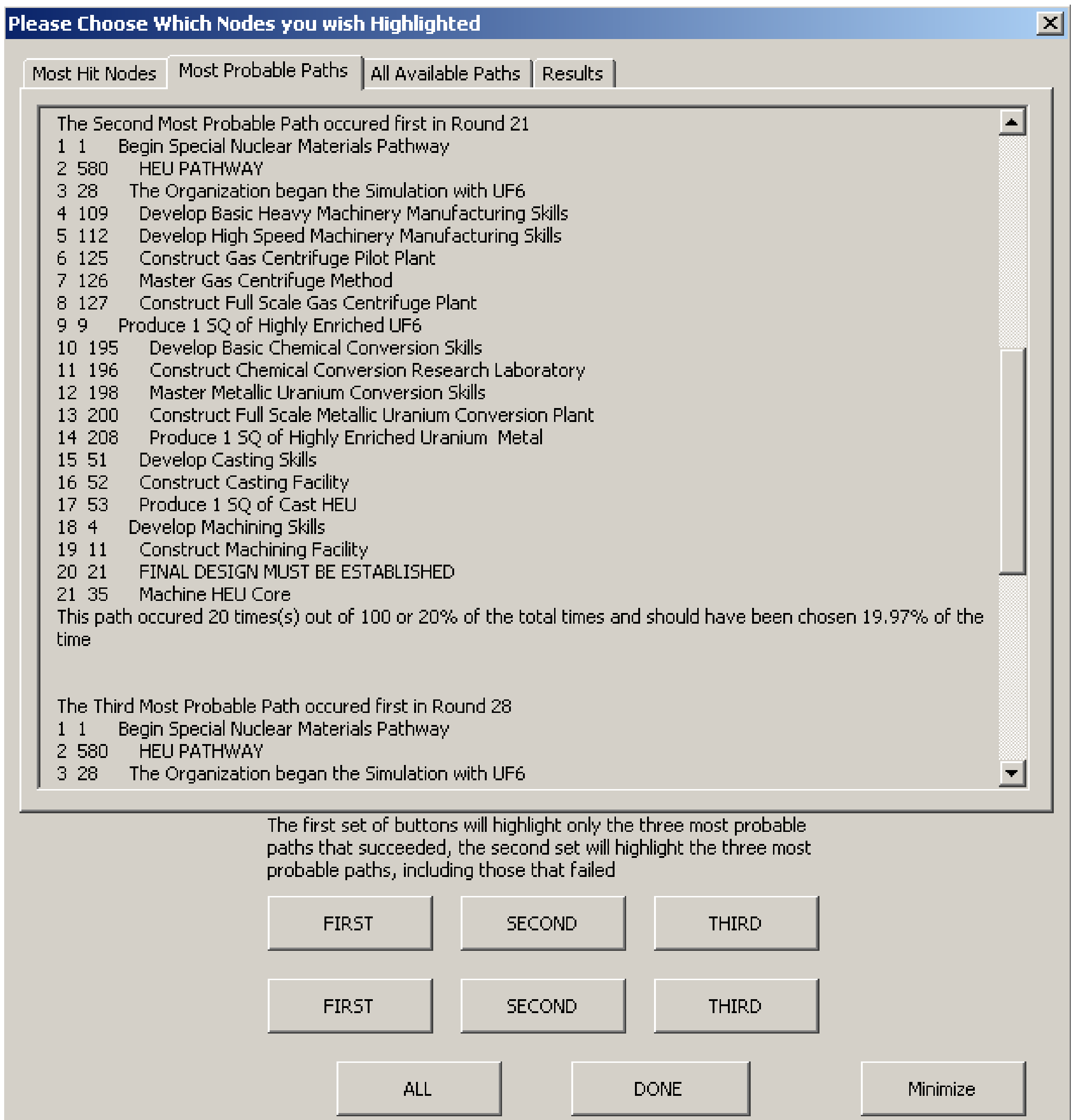
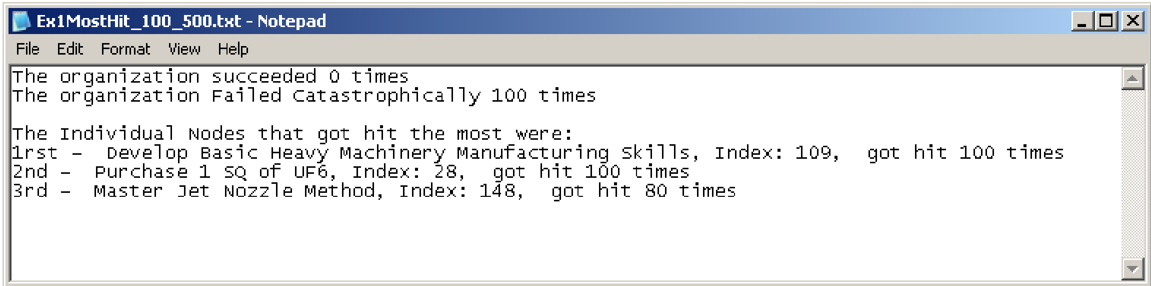


Figure 25. Second output screen from example 1




```
The organization succeeded 0 times
The organization Failed Catastrophically 100 times

The Individual Nodes that got hit the most were:
1rst -  Develop Basic Heavy Machinery Manufacturing Skills, Index: 109,  got hit 100 times
2nd -  Purchase 1 SQ of UF6, Index: 28,  got hit 100 times
3rd -  Master Jet Nozzle Method, Index: 148,  got hit 80 times
```

Figure 26. One of the text files created and saved from example 1

Figure 27 shows that the organization spent almost 30 years (1431 weeks) developing the basic industrial infrastructure required to build the specialized equipment that the enrichment facilities use. Because this activity is not specific to weapons development, the organization is very likely to complete it without raising any suspicions, thus the 30 year time frame with no catastrophic failure. However, once even the beginning of weapons research occurs, the organization is taking so long to complete it that they eventually get noticed and caught.

This result highlights the fact that even something as basic to most countries as a modest industrial capacity is capable of severely hampering the efforts of sub-state actors. This alone does an exceptional job of highlighting the fact that this is not an easy undertaking. Simply being able to machine parts to a high degree of precision is key to producing the entire infrastructure required for this network. This is one aspect of a nuclear weapons program that is often not considered, but still of high importance.

If we begin to include these skill sets for this organization, the end result does not change considerably as the group still gets caught, however, the 30 year time frame spent on basic heavy machinery manufacturing is no longer necessary. Thus, the group begins actual weapons research sooner and gets caught much more quickly.

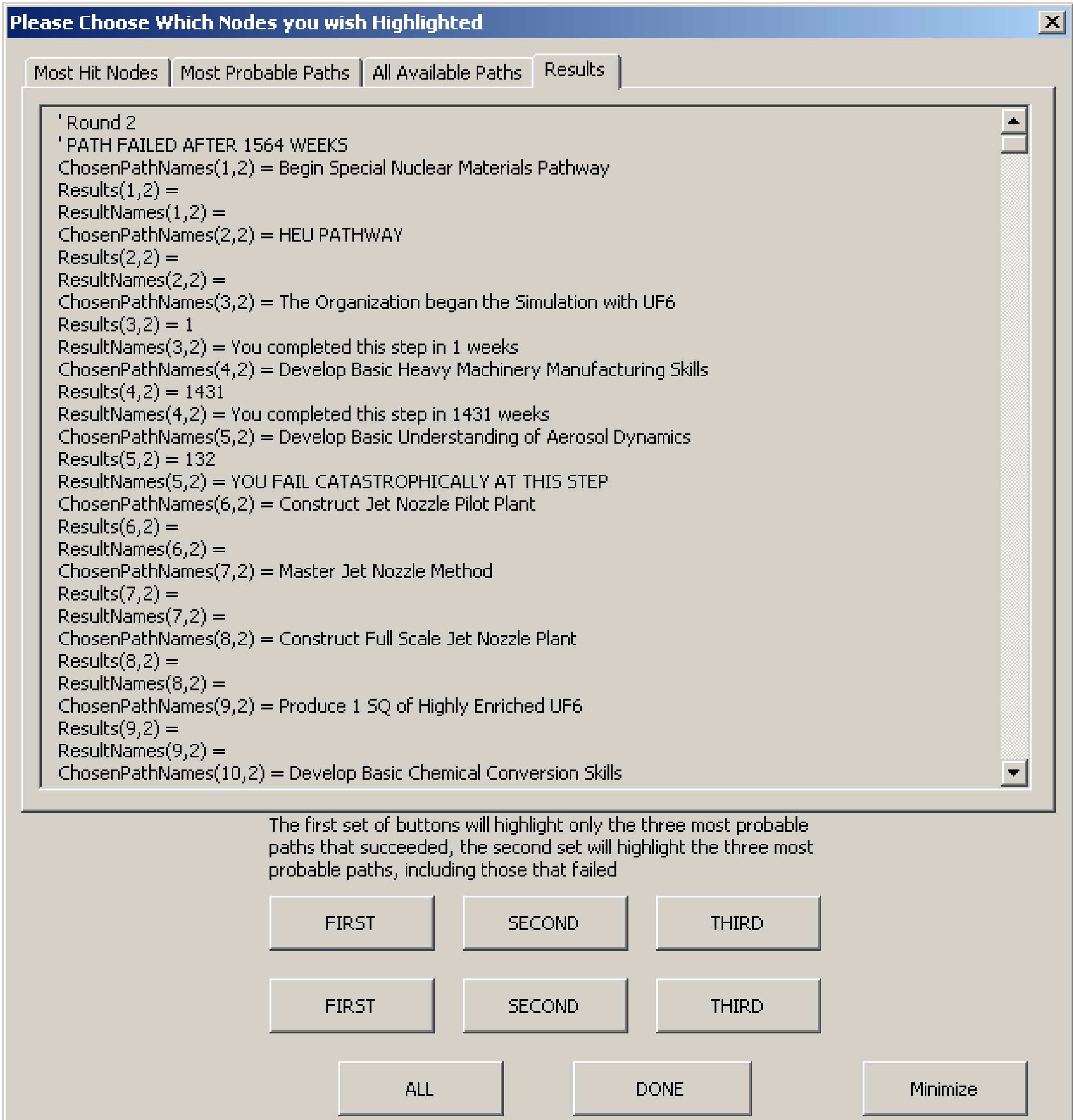


Figure 27. Third output screen for example 1

VI.B. Example 2: Small Organization with Moderate State-Sponsorship

This example problem will consider a similar organization, but one which has some degree of sponsorship from a nation state in the form of access to skill sets. This would be similar to an identical organization in example having the support of a nation such as Iran who could train them in the basics of the various enrichment techniques available. Figure 28 shows the following skills that have been made available:

- Basic Heavy Machinery Manufacturing Skills
- Basic Understanding of Accelerator Physics
- Micro Porous Barrier Manufacturing Skills
- High Speed Machinery Manufacturing Skills
- Basic Understanding of Lasers and Optics
- Basic Understanding of Aerosol Dynamics

The results for this example show that without the encumbrance of having to develop the prerequisite skills, the gas centrifuge method is actually a slight favorite. As Figure 29 and Figure 30 show, the two methods are basically equally as attractive to the organization now. This result occurs because the overall resources for the path as a whole has changed, although not drastically. The resources required to develop high speed machinery skills are fairly large, as it this is a unique skill set not common in other fields. However, aerosol dynamics are much more commonplace. Additionally, even with the basic skill sets, the other enrichment techniques simply require too many resources to accomplish without more experience or facilities already having been obtained by the organization.

It is also important to note that even with this additional head start the organization failed every time in a 500 round example. This of course stems from the fact that even though the organization has managed to obtain certain skill sets before embarking on their weapons program, they still do not have the resources to reliably develop an indigenous program.

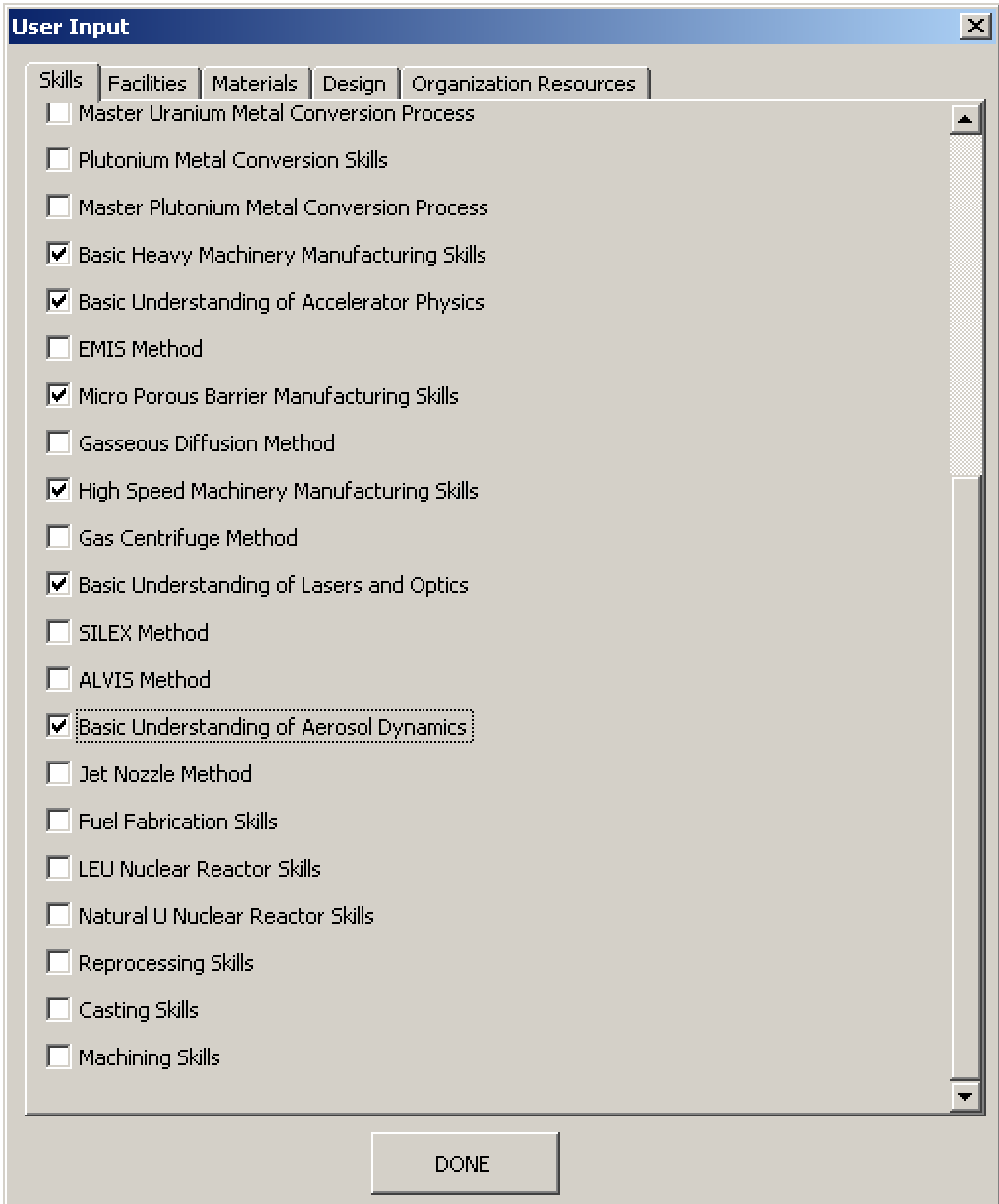


Figure 28. Input screen for example 2

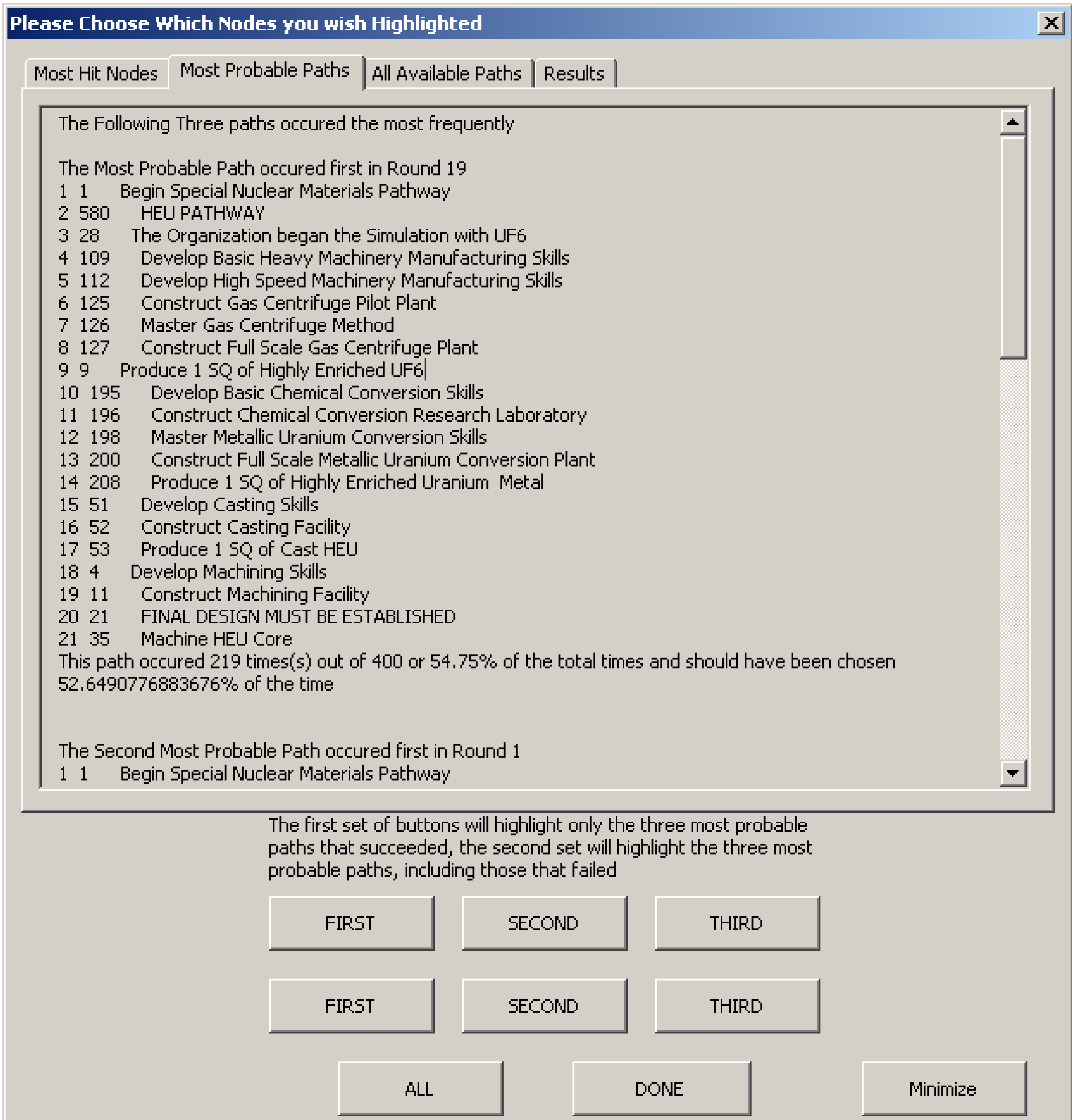


Figure 29. Example 2 output screen

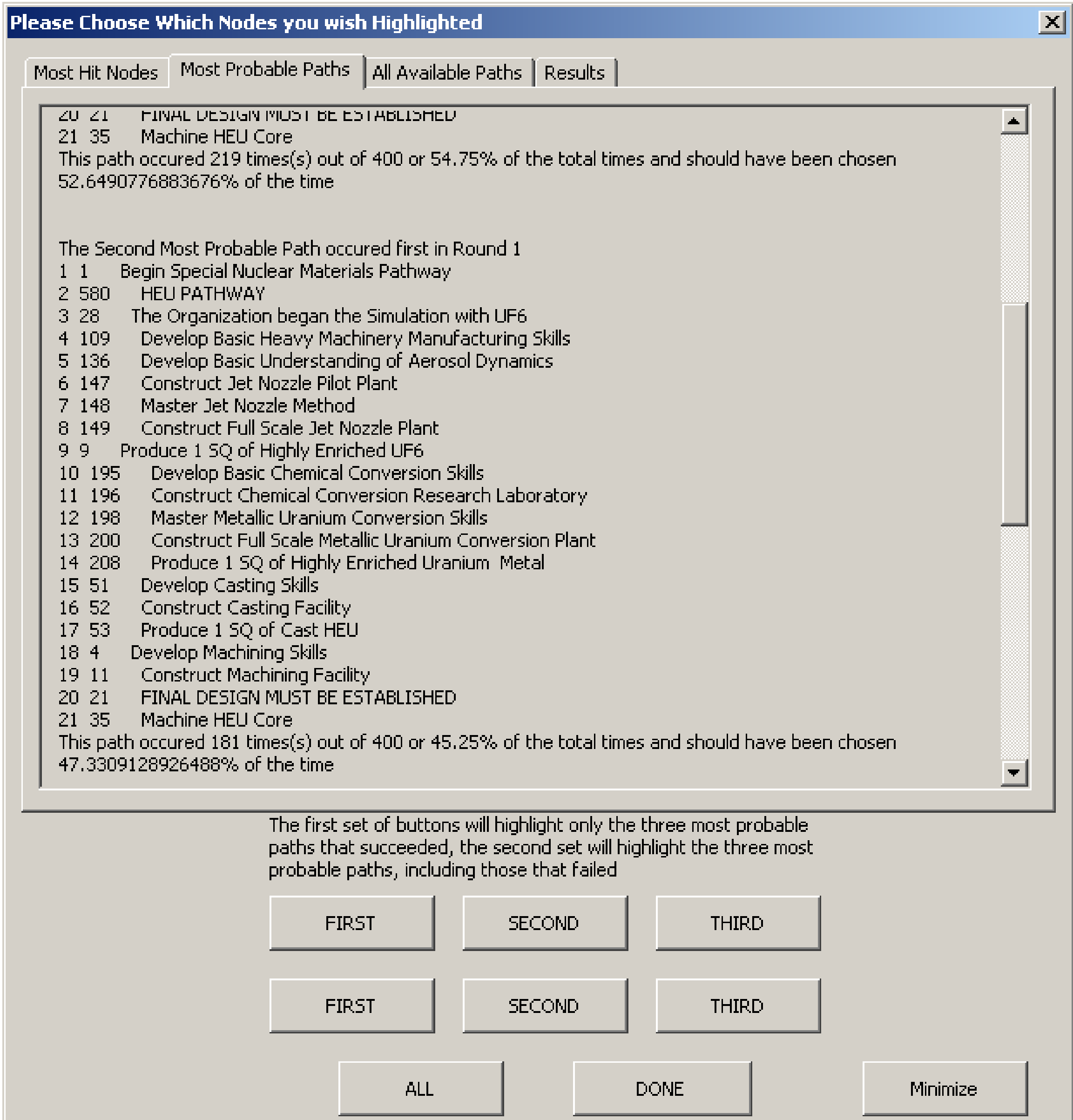


Figure 30. Example 2 second output screen

VI.C. Example 3: Large Organization with Heavy State-Sponsorship

The final example will be of an organization with access to a moderate industrial base (perhaps a state sponsored organization). This organization will have significant resources to devote to producing HEU, and will have already obtained not only uranium Hexafluoride, but access to personnel with experience in all forms of uranium enrichment, along with casting and machining expertise. As can be seen in Figure 30,

Figure 31 and Figure 32 the organization starts out with considerable amounts of all the resources of interest for the available paths:

- 20 PhD level scientists
- 35 Masters level scientists
- 20 Bachelor of science level scientists
- 200 construction workers
- 75 machine operators/technicians
- 1 team of special operations soldiers (although it will not be used anywhere in the simulation)
- Rank 10 of international networking
- 300 square miles of land
- Annual Budget of 500 million U.S. dollars
- 1 SQ of Uranium Hexafluoride
- HEU Weapon Design
- Basic Heavy Machinery Manufacturing Skills
- Basic Understanding of Accelerator Physics
- Micro Porous Barrier Manufacturing Skills
- High Speed Machinery Manufacturing Skills
- Basic Understanding of Lasers and Optics
- Basic Understanding of Aerosol Dynamics
- Casting Skills
- Machining Skills
- Chemical Conversion Research Laboratory
- Gas Centrifuge Pilot Plant
- Jet Nozzle Pilot Plant

Such an organization is most likely to have close ties to a nation state. This type of organization could be considered as a fairly accurate model of a small covert weapons program for a nation state itself. However, if we focus on sub-state groups, this would be similar to the relationship Al-Qaeda shared with the Taliban government that controlled

Afghanistan. If such a relationship were to exist with a country that was more advanced in the nuclear arena, an organization with the resources modeled here could well exist.

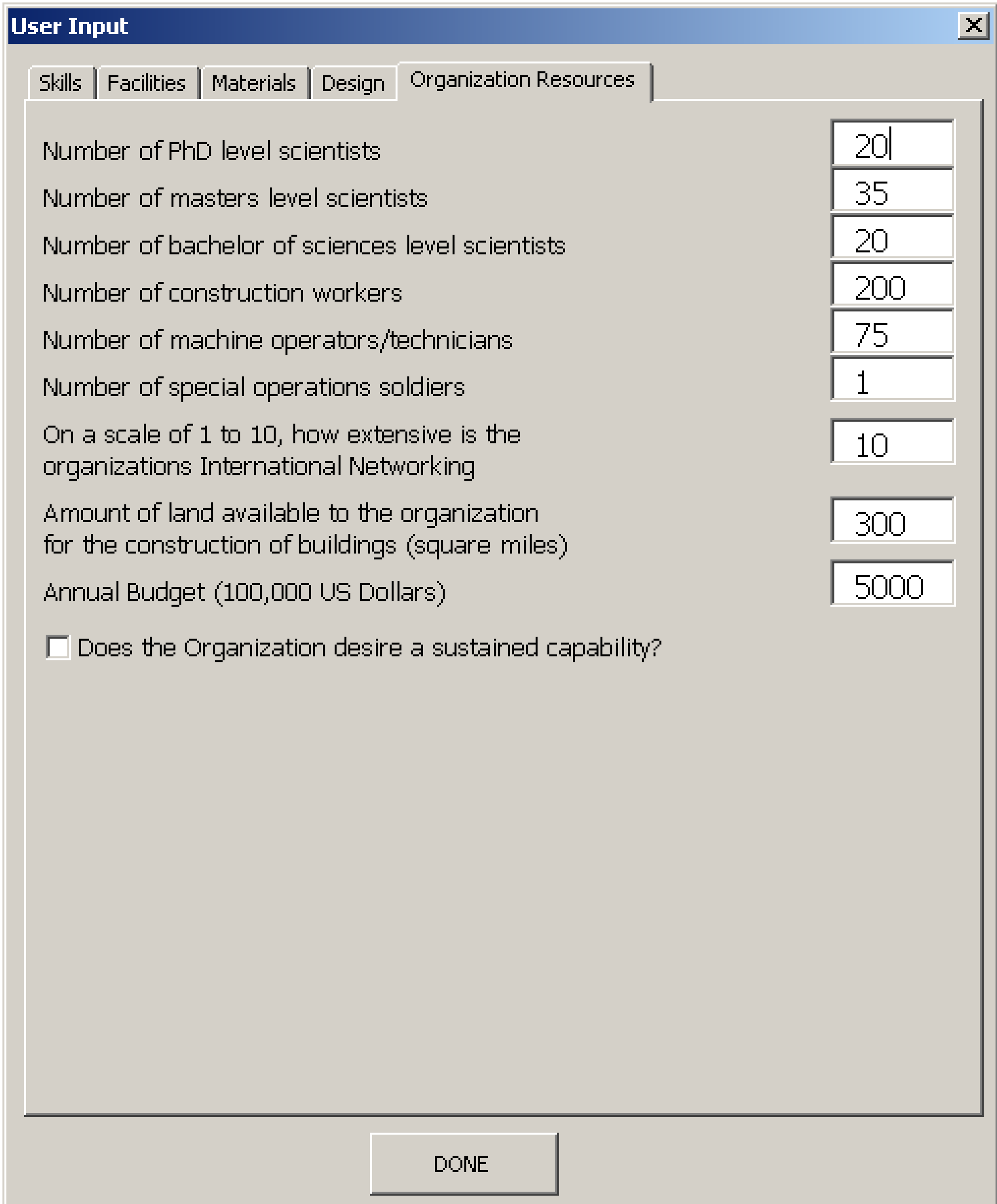


Figure 31. Example 3 first input

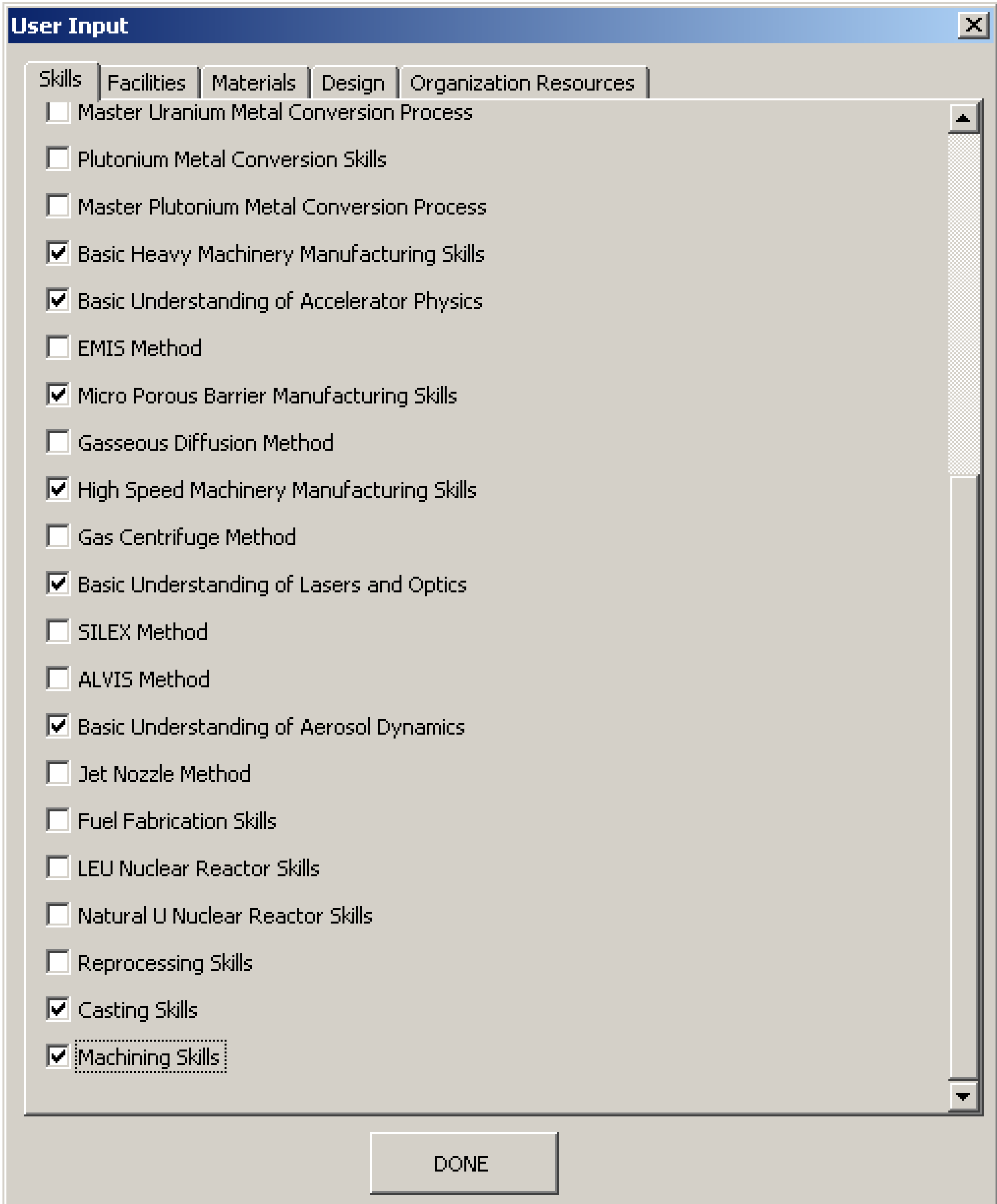


Figure 32. Example 3 second input

The results from this simulation show that even with these resources it is still difficult to produce HEU without being detected. One thing the analyst must always remember is that this organization may continue to operate even after detection under the right circumstances, however that case falls out of the concerns of this program. Regardless, the organization was only successful ~1% of the time in this simulation. The choice of paths is interesting to note as well. With all of the expertise and resources available to the organization, they chose to enrich using the gas centrifuge method as can be seen in Figure 33. This is not surprising in the least, especially considering the fact that all modern enrichment facilities in the world use this method.

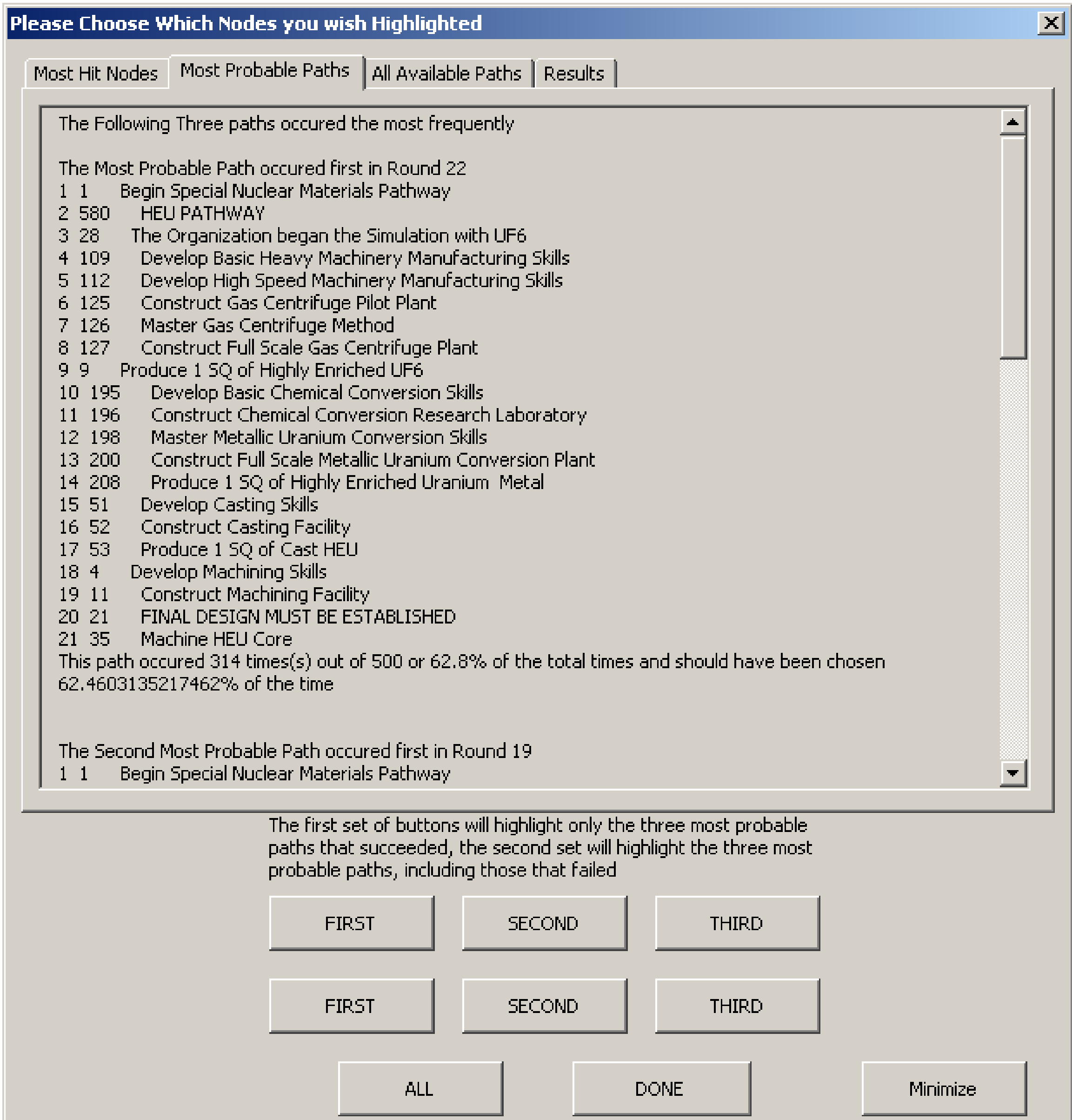


Figure 33. Example 3 output

As these results show, it is relatively easy for the user to enter any organization of interest and determine which paths he is most likely to find attractive, regardless of his success rate on those paths. These results also illustrate that producing special nuclear material is incredibly difficult work. Even when an organization begins the simulation with a modest number of skill sets, facilities, and feed material, it will still require a tremendous influx of resources to successfully complete production.

It should also be noted that the number of rounds the user determines the code to run will effect how long the code will require to complete its analysis. If only a few rounds are specified, then the analysis will run in a matter of tens of seconds, if 100,000 rounds are specified the analysis could take the better part of three days to complete as shown in Figure 34.

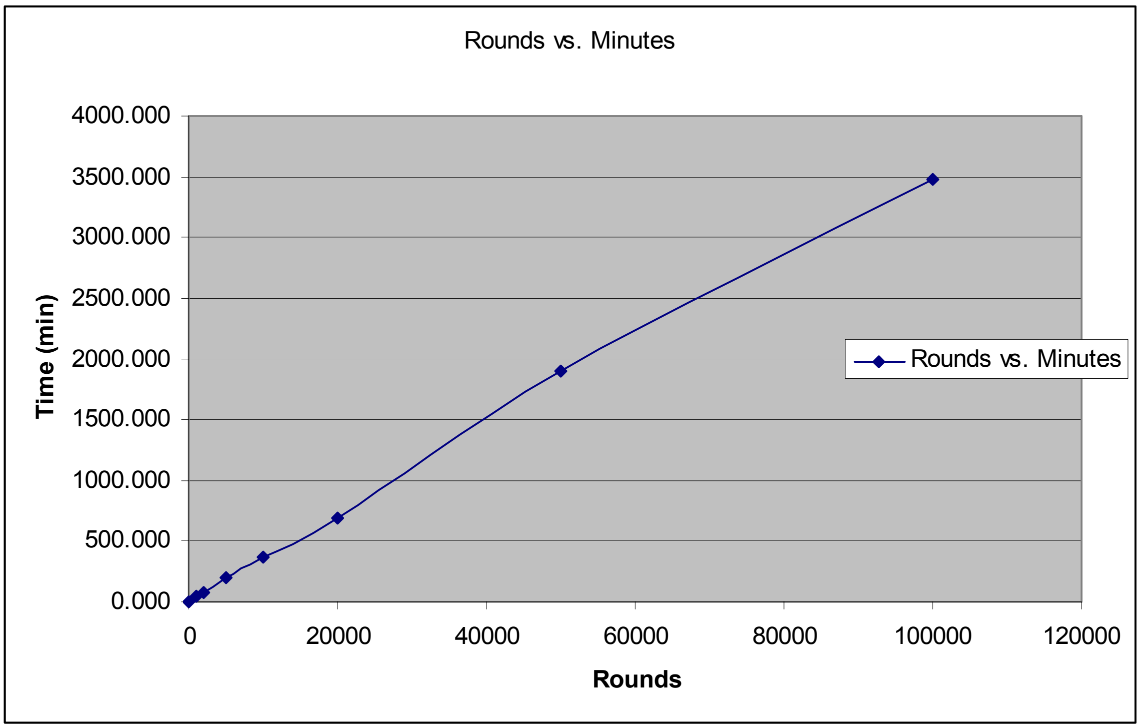


Figure 34. The linear relationship between the number of rounds and the amount of time the program requires to complete the analysis

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CHAPTER VII

CONCLUSIONS

The construction of the nuclear material acquisition network was only the beginning of this work. A method to analyze the pathways a defined organization would take through the network based on intelligent resource based decisions was also developed. The network was built within Microsoft Visio and the coding for the methodology was done in Visual Basic for Application which is already built-in to the Visio macro system. This system was tested to ensure that the solution mechanism provided the expected results for a set of cases.

The results from all of the tests run showed that in order to have any chance of success large amounts of resources must be expended to produce Special Nuclear Material. The processes involved are simply too complex and without heavy assistance from an experienced state entity the chances of any organization accomplishing this task approaches zero. It is interesting to note that one node perhaps taken for granted in many countries provided a considerable hurtle to an organization without access to it, an industrial capacity. The ability to manufacture parts and machinery to strict tolerances is a requirement for the production of SNM, more specifically the facilities that must be built to process the material. Because of the expense of each process step that nuclear material must go through before it is weapons useable it is much more likely that a small organization will attempt to purchase or steal material that is pre-processed. The most likely scenario involves a terrorist organization stealing or purchasing material that must only be mated to the rest of an improvised nuclear device.

While this work only concerns the most likely paths and their chances of success, it should be noted that because of these findings this author feels that if special nuclear material were ever obtained by a small organization it would be a crime of opportunity. These organizations are only likely to succeed if they are able to spend large amounts of resources and even then must begin the simulation with heavily pre-processed material. Because of this, the only scenario which is truly worrisome is one in which they begin the simulation with a state-sponsor that is willing to provide this material.

This work has been of value because it provides an analysis tool that may be used to determine what the resources an organization is gathering or has available to it may tell us about their intentions. It is capable of assisting and providing insight to an analyst in performing his duties. This work may also be used to training exercises to assist in familiarizing incoming analysts without a nuclear related background with the processes that must be accomplished to produce SNM.

The future of this work could include incorporating additional solver schemes to cut down analysis time. While the current Monte Carlo is thorough it can take a considerable amount of time to run. A real-time analysis would allow the user to perform a much more convenient sensitivity analysis. Additional decision making properties could be taken into account as opposed to only using the resources available to the organization. This methodology could also be packaged with other models to ensure that an analyst gets an unbiased view.

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VITA

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